DEPARTMENT OF OCEAN ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

THE APPLICATION OF ROBOTIC ARC WELDING TO SHIPBUILDING

by

NICHOLAS A. KOREISHA

OE
SM (OSM)

Course XIIIA
June 1984

Thesis
K795

THE APPLICATION OF ROBOTIC ARC WELDING TO SHIPBUILDING

by

NICHOLAS ALEXIS KOREISHA

S.B., Massachusetts Institute of Technology
(1976)

Submitted in partial fulfillment of the requirements

for the degrees of

OCEAN ENGINEER

and

MASTER OF SCIENCE IN OCEAN SYSTEMS MANAGEMENT

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1984

© Massachusetts Institute of Technology 1984

The author hereby grants to the United States Government and its agencies permission to reproduce and to distribute copies of this thesis document in whole or in part.

Thesis
K795

THE APPLICATION OF ROBOTIC ARC WELDING TO SHIPBUILDING

by

NICHOLAS ALEXIS KOREISHA

Submitted to the Department of Ocean Engineering on May 11, 1984 in partial fulfillment of the requirements for the Degrees of Ocean Engineer and Master of Science in Ocean Systems Management.

ABSTRACT

This country's economically depressed shipbuilding industry is seeking to modernize facilities to improve its competitiveness. The feasibility of using future robotic arc welding systems to help achieve this goal is explored.

A general survey of shipyard activities was made to identify areas of potential robot application. Based on this study and information on current research, ship flat panel assembly was identified as a potential application area requiring additional attention.

A flat panel assembly line was modelled for the production of tanker panels and analyzed for various robotic arc welding systems. Cost projections were made to assess the potential economic benefits for the required productive capacity of each alternative.

It was concluded that flat panel assembly has some economic potential for the introduction of robotic arc welding and recommended that further exploration of this and other applications be undertaken.

Thesis Supervisor: Koichi Masubuchi
Title: Professor of Ocean Engineering and Materials Science

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

LIST OF FIGURES

LIST OF FIGURES (Cont'd.)

LIST OF TABLES

ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to many who made this thesis possible, including other researchers whose work helped to guide his efforts.

The following people are thanked for the knowledge, support, inspiration, and advice they provided.

J. Agapakis	J. Newcomb
J. Berger	R. Ramsay
M. Bernier	J. Rice-Koreisha
K. Masubuchi	L. Sayegh
F. McConnell	T. Somers

CHAPTER 1

INTRODUCTION

The American shipbuilding industry, struggling for its economic survival, is seeking to modernize its operations to improve productivity and competitive position. The purpose of this thesis is to explore the potential feasibility of future robotic arc welding systems as a means of contributing to the achievement of this goal.

The general methodology undertaken was to first survey the current state of shipbuilding in this country, and then identify areas of applications for the potential use of robotic welding. The second objective was to narrow the study's focus on one construction area that appeared to offer good prospects, and then qualitatively and quantitatively estimate the impact that robot systems could have on it. It was hoped that by comparing the potential effects of alternative robot concepts, some conclusions might be reached about their future technological and economic benefits, so that areas for further study might be identified.

Chapter 2 presents an overview of American shipbuilding, citing its condition and position, vis-a-vis the rest of the world. Coupled with the presentation of a possible approach to industry revitalization, a context for technical and economic examination is formed.

In Chapter 3, various methods of ship construction are explained. Requirements for welding in the different production processes, among these methods, are studied to provide the foundations upon which major robot application areas can be identified.

Selection criteria for robotic arc welding are discussed in Chapter 4, considering technical, ship design, and human requirements.

Chapter 5 identifies ship construction applications for more in-depth examination, based on economic and technological requirements.

A close examination of a fundamental shipbuilding process, (flat panel assembly), is presented in Chapter 6, along with various robotic arc welding systems. The methodology of predicting their impact on the systems and its economic viability are discussed in some detail.

The actual process and economic models used for analysis, and their results, are shown in Chapters 7 and 8. A tanker structure was selected for model input data to reflect ship design trends of improved producability.

Only general conclusions could be reached on the practicability of robotic arc welding in the flat panel assembly process. Nevertheless, insight was gained on critical issues, and topics of future research are recommended.

CHAPTER 2

THE ECONOMIC ENVIRONMENT OF AMERICAN SHIPYARDS

2.1. An Overview of the Shipbuilding Industry

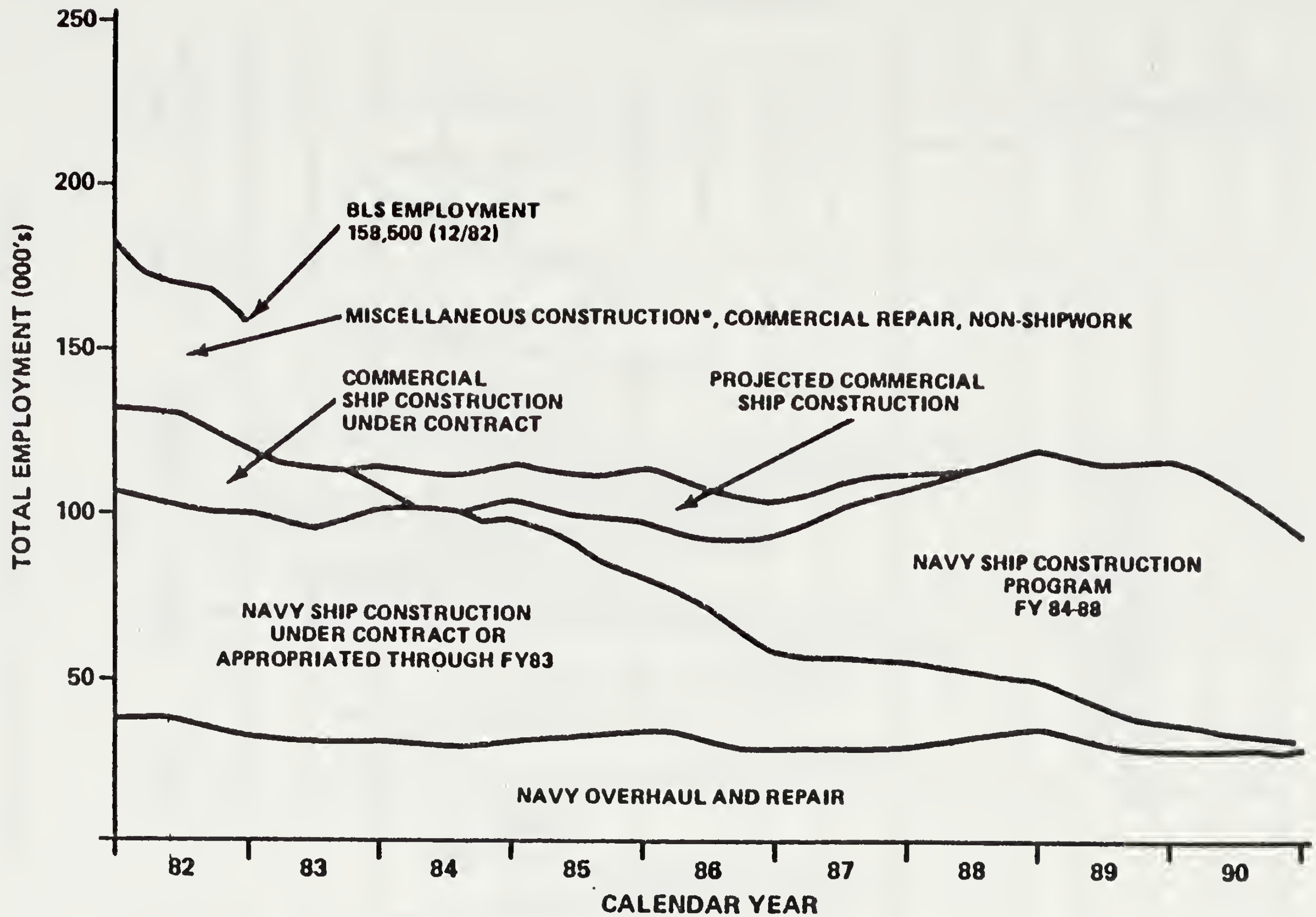
The shipbuilding industry of the United States has been sagging continually since the end of the 1940's. Many reasons, in various combinations can be cited to cause the decline of this industrial base. Included are rising competition from developing foreign nations that enjoy economies of production, American business practices and government policies that do not sufficiently encourage increases in competition and productivitiy, and a cyclical demand for ships. It is important to appreciate the environmental factors affecting capital expenditures for advanced shipbuilding technology.

The U.S. Navy's Director of Maritime Affairs and Shipbuilding Technology has characterized the U.S. shipbuilding industry as monopsonistic due to the high proportion of Navy construction in private yards [1]. As an example, in 1982 the Navy awarded contracts for construction and conversion to private shipyards worth approximately \$4.5 billion. Naval repair work provided employment for some 30,000 private shipyard workers.

In contrast, merchant shipbuilding was virtually non-existent in that year: contracts for three small ships were awarded with a value of \$104.6 million. Commercial ship repair and conversion was estimated at \$1.5 billion in 1982.

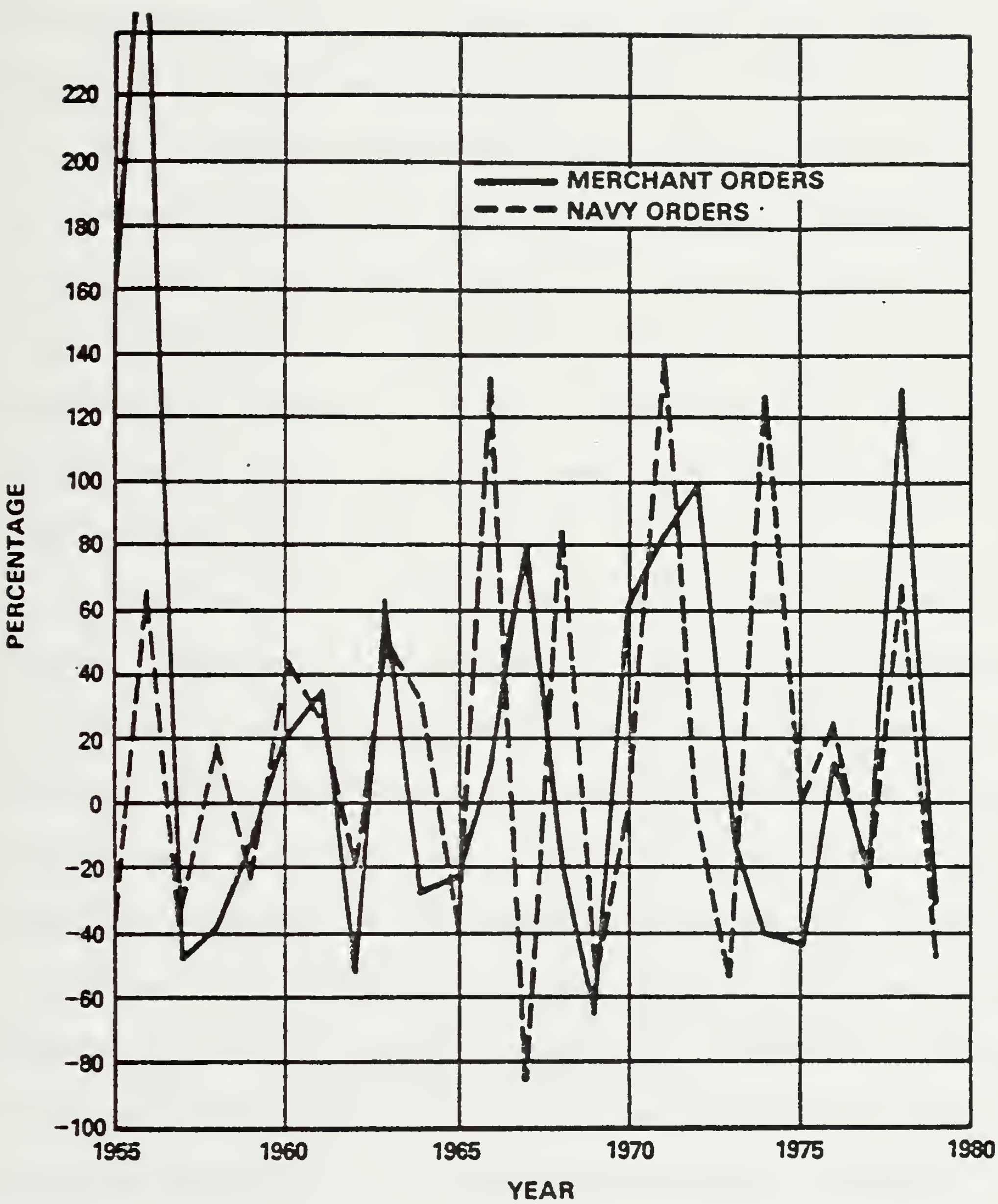
The active U.S. shipbuilding base, consists of 27 shipyards that build or are interested in building naval or merchant ships. These 27 yards employ about 70 percent of the U.S. shipyard population. The total number of employees has continually decreased in recent years and the trend is predicted to continue. A recent forecast of the shipbuilding industry's workload is depicted in Figure 2.1. In 1982, the industrial base production workers were engaged in 62 percent naval ship construction, 15 percent naval ship repair, 12 percent commercial shipbuilding, and 6 percent commercial ship repair. Of the total industry workload for that year, 36 percent was Navy new construction work and 20 percent Navy overhaul and repair. And as future commercial shipbuilding dwindles, one can accordingly expect the industry's dependency on Navy work to grow.

This unfortunate situation is of considerable concern to all involved in shipbuilding, including the Navy, which must relay on the health of this private industrial base for its hardware. The immediate issues for the industry are those of survivability and contraction, rather than capacity or technical credibility. The risks of engaging in ship construction and investing large sums of capital in the required production facilities are exemplified by Figure 2.2, showing erratic levels of demand from 1955 to 1980. Another important indicator of investment risk is the asset/sales ratio of an industry. This is a measure of how many dollars of business can be generated by one dollar of assets. This ratio is influenced by the technological state-of-the-art required to execute a ship construction or repair program [2].



U.S. Shipbuilding Industry Workload Forecast

FIGURE 2.1[1]



Annual Percentage Changes in Ship Orders

FIGURE 2.2[2]

As a means of comparison, a 1:10 ratio is said to represent low-technology and conversely, a 10:1 ratio indicates high-technology investment. Ramsay [2] reports that the aggregate European (NATO) defense-related industries approximate a ratio of 1:1, while the average of U.S. defense-related industries approximates a ratio of 1:2. U.S. commercial shipbuilding and repair have ratios of 1:4 and 1:10 respectively. Apart from the low-technology investment required of the latter, the workload stability, simplified contracting, and high profits contribute to the attractiveness of commercial ship repair. Consequently, the normal strategy of shipbuilders is to maintain a healthy repair capability to help smooth out production levels that would otherwise be erratic.

Another measure of industry efficiency is the value added by the builder. Approximately 66 percent of the value of a commercial ship constructed in the United States is comprised of value added by the shipyard. This means that labor, amortized investment and other overhead costs constitute some 2/3 of the cost (value) of the ship. Materials, components, and procured machinery account for only 1/3 of the cost. U.S. Bureau of the Census data from 1977 show that when compared to six other comparable heavy U.S. industries, shipbuilding is by far the most labor intensive. Figure 2.3 also shows that while the ratio of production to non-production workers is highest in shipbuilding, payroll accounts for 63 percent of the value added. The resultant value added per production manhour is the lowest among heavy industries.

Indices of Labor Cost in Shipbuilding and Comparable Industries

INDEX	INDUSTRY (SIC CODE)						
	3731	3312	3441	3494	3531	3541	3721
1. PAYROLL/EMPLOYEE	$18,953	$26,045	$16,371	$17,185	$21,217	$20,659	$23,719
2. PRODUCTION WORKERS AS PERCENT OF TOTAL EMPLOYEES	80	78	75	69	69	66	55
3. AVERAGE HOURLY EARNINGS OF PRODUCTION WORKERS	$8.77	$13.68	$7.21	$7.80	$10.60	$9.00	$10.14
4. VALUE ADDED/EMPLOYEE	$30,105	$46,245	$31,353	$40,936	$47,173	$46,006	$51,945
5. PAYROLL AS PERCENT OF VALUE ADDED	63	56	52	42	45	45	46
6. VALUE ADDED/PRODUCTION WORKER HOUR	$18.97	$32.26	$21.06	$30.27	$36.60	$33.90	$47.10

SOURCE: U.S. BUREAU OF THE CENSUS

STANDARD INDUSTRIAL CODES (SIC):

3731 – SHIPBUILDING AND REPAIRING
3312 – BLAST FURNACES, STEEL WORKS
3441 – FABRICATED STRUCTURAL METAL
3494 – VALVES AND PIPE FITTINGS
3531 – CONSTRUCTION MACHINERY
3541 – MACHINE TOOLS
3721 – AIRCRAFT

FIGURE 2.3 [5]

These indices attest to three observations of American shipbuilding:

1. It is a labor intensive industry

2. It is a capital intensive industry

3. It is a relatively inefficient industry.

2.2. Shipbuilding Productivity

The productivity of U.S. shipbuilding relative to shipbuilding in the rest of the world, has declined dramatically.

Defining productivity can be elusive, though the term is commonly used in everyday management decision-making. Ideally, productivity should be indexed by measuring physical output per unit of total resources utilized in production. However, accurately measuring output or input can be a difficult problem. Ships are of diverse scale, function, and construction, and are not easily correlated among different types. Also, the increasing complexity of warships complicates the measurement of productivity trends in time.

Perhaps the most accurate overall index of productivity in the shipbuilding industry would be profitability in an economic sense. The asset/sales ratio, already mentioned, could serve as this measure providing the industry profits were earned in a competitive environment, one in which neither buyers or sellers possessed power over price and in which both were subject to economic incentives. However, these characteristics do not generally prevail in the U.S. shipbuilding industry.

An alternative indicator for productivity assessment is value added per production worker which measures the quality of capital and

labor employed together with the quantity of capital assets.

The low ranking of shipbuilding's value added per worker among other industries already cited can be related to a host of factors. Included are lagging production capital investment, diminished devotion to work ethic, labor usage, turnover, etc., all due in part to uncertainties in the long-term future of U.S. shipbuilding. In making inter-industry comparisons, it should be recognized that ship construction will never benefit from mass-production processes to the degree of the airplane, auto, and other consumer good industries. Thus a more objective measure might be the comparison of U.S. and foreign shipbuilding industries.

To account for the many factors contributing to the decline of American and the ascent of foreign shipbuilders, Ramsay [2] suggests a total-system approach broadly focused on the shipbuilding industry's form, behavior, and productivity. He asserts that it is insufficient to analyze only the readily quantifiable elements such as labor rates, capital investment, manhours per ship, etc. An appreciation of socio-economic and cultural variables, government-business alliances, national industrial goals, etc. are also required for international comparisons among shipbuilding industries.

A 1978 technology survey of major U.S. shipyards [3] noted that many billions of dollars had been invested in the Japanese shipbuilding industry subsequent to World War II, resulting in the production of merchant ships in less time, fewer manhours, and less cost than that required in the U.S. This MARAD-sponsored report addressed 70 technology elements in each major U.S. shipyard and found technology

shortfalls in 51 elements, relative to foreign competion in merchant shipbuilding. The majority of these shortcomings, listed in Table 2.1 are applicable to complex warship construction as well. The results of the report's comparative analysis, shown in Figure 2.4, demonstrate significant shortcomings in all categories except outfitting (Category B) and operating systems (Category H). The most serious shortfalls were in the categories of pre-erection activities and environmental amenities. While these results were directly related to merchant ship production, they give good indication of shortfalls in warship production as well.

While no elements of American shipbuilding are heavily capitalized in technology, relative to other industries and a number of foreign shipbuilders, a trend for improvement is underway. Recent implementation of computer-aided layout and production processes, design, and management, automatic and semi-automatic welding equipment, and larger lift and handling equipment to accommodate the increased use of modular construction are evidence of such a trend. However, pressures to maintain a labor-intensive posture will remain in U.S. shipyards because of the difficulty in applying mass-production techniques under present low-volume circumstances. This lack of incentive for capital investment is exacerbated by the American manager's comparative preoccupation with short-term investment payback and financial posture. Additionally, six of this nation's nine combatant-capable shipbuilding yards are subsidiaries of large diversified corporations. Thus the needs, priorities, and goals of these yards are intimately and inextricably tied to those of their parent company. As a matter of investment

A: STEELWORK PRODUCTION
- A1 PLATE STOCKYARD AND TREATMENT
- A2 STIFFENER STOCKYARD AND TREATMENT
- A3 PLATE CUTTING
- A4 STIFFENER CUTTING
- A5 PLATE AND STIFFENER FORMING
- A6 SUB ASSEMBLY
- A7 FLAT UNIT ASSEMBLY
- A8 CURVED AND CORRUGATED UNIT ASSEMBLY
- A9 3-D UNIT ASSEMBLY
- A10 SUPERSTRUCTURE UNIT ASSEMBLY
- A11 OUTFIT STEELWORK

B: OUTFIT PRODUCTION AND STORES
- B1 PIPEWORK
- B2 ENGINEERING/MACHINE SHOP
- B3 BLACKSMITHS
- B4 SHEETMETAL WORK
- B5 ELECTRICAL
- B7 RIGGING
- B8 MAINTENANCE
- B9 GARAGE
- B10 GENERAL STORAGE
- B11 AUXILIARY STORAGE

C: OTHER PRE-ERECTION ACTIVITIES
- C1 MODULE BUILDING
- C2 OUTFIT PARTS MARSHALLING
- C3 PRE-ERECTION OUTFITTING
- C4 BLOCK ASSEMBLY
- C5 UNIT AND BLOCK STORAGE

D: SHIP CONSTRUCTION AND INSTALLATION
- D1 SHIP CONSTRUCTION
- D2 ERECTION AND FAIRING
- D3 WELDING
- D4 ON-BOARD SERVICES
- D5 STAGING AND ACCESS
- D6 PIPEWORK
- D7 ENGINE ROOM MACHINERY
- D8 HULL ENGINEERING
- D9 SHEETMETAL WORK
- D11 ELECTRICAL
- D12 PAINTING
- D13 TESTING AND COMMISSIONING
- D14 AFTER LAUNCH

E: LAYOUT AND MATERIAL HANDLING
- E1 LAYOUT AND MATERIAL FLOW
- E2 MATERIALS HANDLING

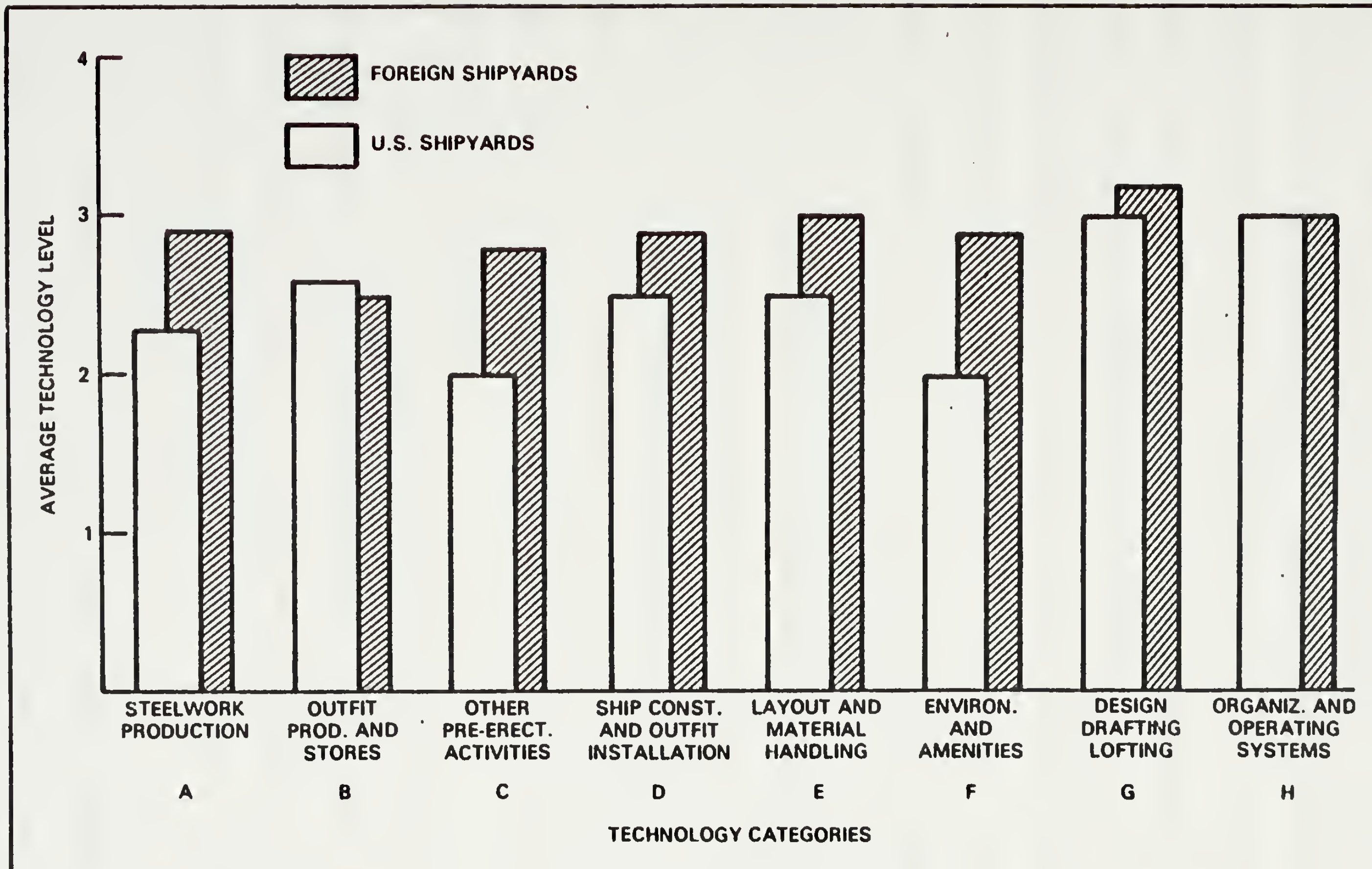
F: AMENITIES
- F1 GENERAL ENVIRONMENTAL PROTECTION
- F2 LIGHTING AND HEATING
- F3 NOISE, VENTILATION AND FUME EXTRACTION
- F4 CANTEEN FACILITIES
- F5 WASHROOMS/WCs LOCKERS
- F6 OTHER AMENITIES

G: DESIGN, DRAFTING, PROD. ENGR'G & LOFTING
- G1 SHIP DESIGN
- G2 STEELWORK DRAWING PRESENTATION
- G3 OUTFIT DRAWING PRESENTATION
- G4 STEELWORK CODING SYSTEM
- G5 PARTS LISTING PROCEDURES
- G6 PRODUCTION ENGINEERING
- G7 DESIGN FOR PRODUCTION
- G8 DIMENSIONAL & QUALITY CONTROL
- G9 LOFTING METHODS

H: ORGANIZATION AND OPERATING SYSTEMS
- H1 ORGANIZATION OF WORK
- H2 CONTRACT SCHEDULING
- H3 STEELWORK PRODUCTION SCHEDULING
- H4 OUTFIT PRODUCTION SCHEDULING
- H5 OUTFIT INSTALLATION SCHEDULING
- H6 SHIP CONSTRUCTION SCHEDULING
- H7 STEELWORK PRODUCTION CONTROL
- H8 OUTFIT PRODUCTION CONTROL
- H9 OUTFIT INSTALLATION CONTROL
- H10 SHIP CONSTRUCTION CONTROL
- H11 STORES CONTROL
- H12 PERFORMANCE & EFFICIENCY CALC.
- H13 COMPUTER APPLICATIONS
- H14 PURCHASING

Shipbuilding Technology Elements

TABLE 2.1[1]



Comparative Shipbuilding Technology Levels

FIGURE 2.4[2]

strategy, the parent corporations have greater incentive to invest retained earnings for capital improvement programs in other subsidiaries offering greater potential return-on-investment at less risk.

Past governmental policies of the United States have not encouraged capital investment, either. The Merchant Marine Act of 1936 was enacted to foster the development of a Merchant Marine fleet sufficient to carry the nation's domestic and a substantial part of its foreign waterborne commerce, and to serve as a naval and military auxiliary in time of war or national emergency [2]. This was at a time when the American merchant fleet was far behind those of other nations in size and age, at a time of growing political tension in Europe. The Act provided for the government to pay Construction Differential Subsidy (CDS) to private American shipowners, up to a limit of 50 percent of construction cost to make up the difference between U.S. and foreign shipbuilding costs. Such subsidies were to be repaid out of one-half of any profits in excess of 10 percent of the capital necessarily employed in the business.

An Operational Differential Subsidy was also made available, the amount depending on costs and competition of particular routes. ODS awards were typically about 75 percent of operating cost differential. The availability of these funds since their inception has helped provide for the short-term survival of U.S. yards. But their failure to provide incentive for productivity improvement through capital investment has caused long-term harm to the competitive position of the industry.

Fortunately, recent political trends show more favorable attention to the long-term plight of shipyards. CDS is now recognized for its deleterious effects and its elimination appears certain. The Congress is currently seeking to replace it with supportive legislation that will effectively encourage capital investment for shipbuilding productivity improvement. The U.S. Navy is also playing a part in promoting shipbuilding productivity by investing R and D monies in its Navy Manufacturing Technology (MANTECH) Program sponsored by the Naval Material Command.

2.3. A Cooperative Approach to a Revitalized Shipbuilding Industry

In contrast to the economic environmental factors and past U.S. Government policies that have, in effect, hindered shipyard capital investment, shipbuilding industries in other nations have been able to develop and maintain healthy capital bases by exploiting advantages (such as cheap labor rates) and/or by securing the cooperation and support of their governments.

The importance of participation and cooperation among government, labor, and industry can be made clear by a short digression, explaining the phenomenon of the post-war Japanese shipbuilding industry. This success story is founded on the concepts of national industrial policy and a progressive corporate culture.

After World War II, Japan adopted a national policy to coordinate industrial reconstruction. Products and industries that were considered necessary for regaining international competitive strength were chosen to spearhead reconstruction and expansion efforts. The government,

in concert with industry, assessed the manufacturing technology needs that would be needed to secure competitive position, and tasked private firms to acquire that technology from abroad or through internal research and development. All licensing agreements between foreign licensors and Japanese licensees were screened by the Japanese government to insure contribution to public (national) goals. To support domestic R and D, educational institutions were tasked to meet the growing demand for science and engineering graduates.

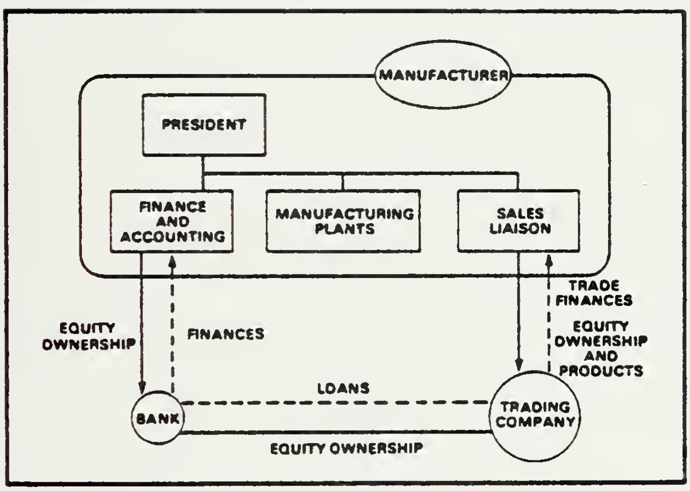
The shipbuilding industry was chosen to spearhead the development of export-oriented heavy industries. The government supported shipbuilding by promoting organizational groupings of various manufacturing firms around leading private banks and trading companies. By channeling 100 percent government financing of ship purchases to shipping firms, through the banks of these industrial combines (called "zaibatsu"), shipyards were induced to ready their production facilities for planned, guaranteed orders. The yards themselves were left to compete for these orders on the basis of price, quality, and delivery schedule, Thus, shipyards were provided incentive to reinvest profits to renew facilities and improve production processes. Technological innovations oriented toward labor and raw material savings, decreased the number of production processes required to construct a ship by as much as 35 percent [2].

Increased investment in gigantic drydocks and berths fostered the industry's innovation of the VLCC and the ULCC. Joint study groups of engineers working for different firms, coupled with the government's establishment of the Ship Technology Institute in 1950 helped to freely diffuse product and process innovation throughout the

industry. Much of the huge sums required for capital investment was channeled by lending banks through large trading firms. The trading companies borrowed heavily on their credit from banks and loaned out funds to manufacturing firms, to cushion risk to banks. This widespread practice insured that the growth of trading companies was strongly related to the economic viability of its associated manufacturing firms, including shipyards. The three-way linkage of these zaibatsu is described in Figure 2.5.

The cooperation of labor was also required for economic success. This was fostered by the Japanese practice of lifetime employment, resulting in a stable, well-trained workforce, and a system of management-employee relations that recognized and supported the basic needs of the worker. By replacing fear of layoff as a means of motivation with guaranteed employment and participation in management and profit-sharing, the worker was provided positive inducement to help improve the firm's productivity. By cultivating the corporate climate and labor-management relations so that commitment to employee welfare was demonstrated, the individual's commitment to the firm's goals and future was secured.

While much of the success of Japan's shipbuilding renaissance depended on the character of its people, the importance of cooperative government-led participation, in any society, cannot be denied. Programs under the sponsorship of the U.S. Government and the Society of Naval Architects and Marine Engineers' joint panels and committees help to foster some cooperation and concern for the long-term development of shipbuilding technology. Industry and government leaders must decide



Japanese Business Linkages

FIGURE 2.5 [2]

if current efforts are sufficient to restore the shipbuilding industry or whether more intensive, cooperative means are required [2].

CHAPTER 3

STATE-OF-THE-ART SHIP FABRICATION

3.1. Purpose

The purpose of this chapter is to introduce the general methods and production stages involved in ship construction and the welding methods used.

3.2. Ship Production Methods

Modern shipyards employ multistage assembly line techniques as much as possible to produce ships. Traditional methods of hull fabrication, followed by launch and outfitting have changed radically. The limited availability of installed building positions (drydocks or ways) present a bottleneck to the overall production flow of a shipyard. Post-launch outfitting frees these critical positions for the construction or repair of other vessels.

Building position time is further reduced by increased use of structure assembly in shops and staging areas. These pre-fabricated panels can then be fitted, tacked, and production welded in dock or on ways. This pre-fabrication stage is commonly termed assembly stage.

By adding an additional stage of prefabrication, called pre-erection or grand, block, or module assembly, such that numerous panels are fitted and welded into a section of the ship structure (or module) prior to transport to the dock position, further reductions to required duration in building position are gained. Of course large capacity cranes and handling devices, rated in the hundreds of tons, are required to lift and position these modules.

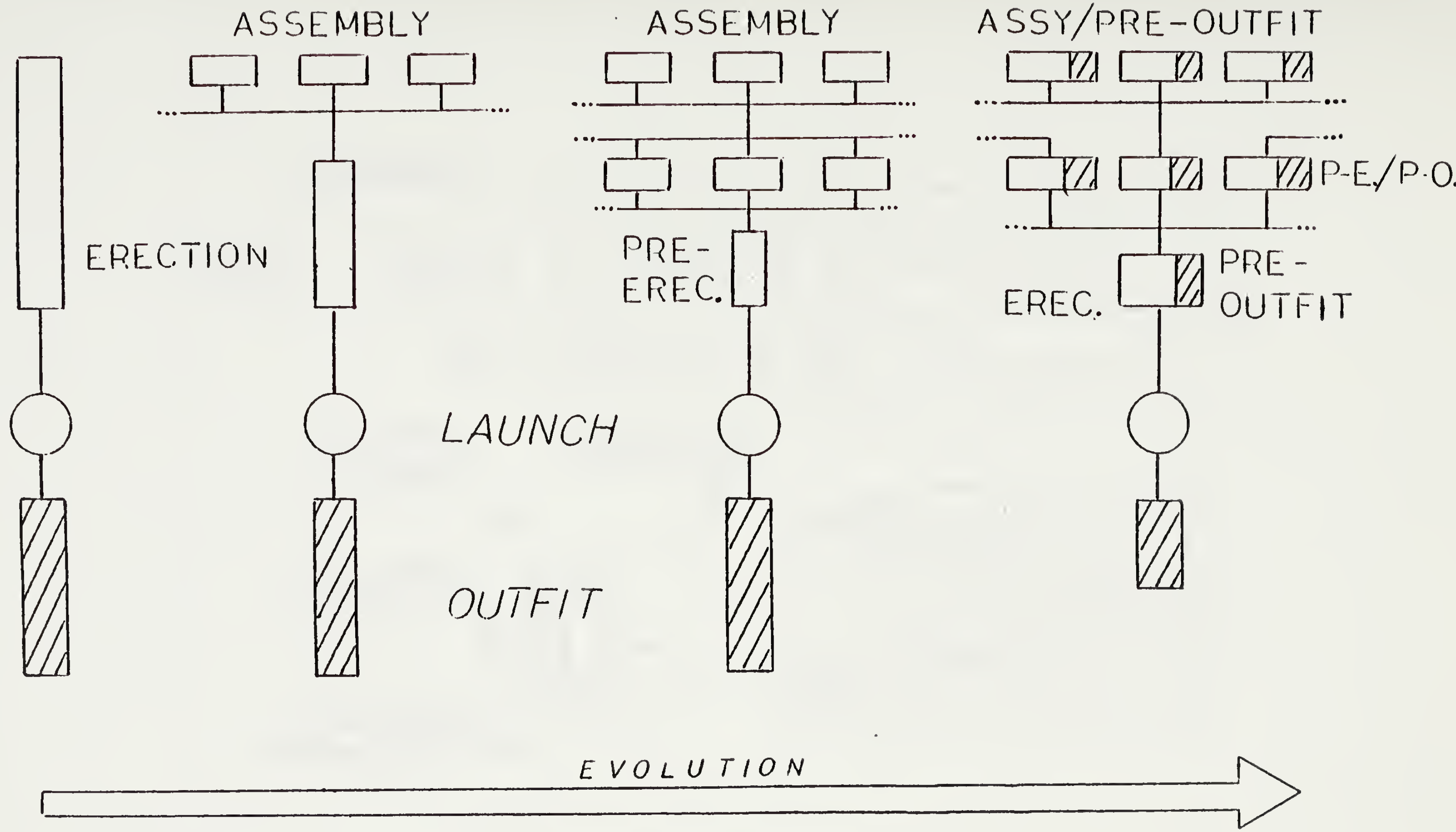
Total construction duration is further reduced by accomplishing as much outfitting as possible during slack periods of structural prefabrication. The key benefit, in addition to reduced total construction duration, is increased outfitting productivity, due to improvements in accessibility at earlier assembly stages. This technique is known as pre-outfitting.

In cases where outfit requirements are complex or extensive, such as naval combatants and passenger liners, pre-outfitting becomes a critical factor to cost reduction. Some 51 percent of shipyard labor costs are due to fitting-out operations on U.S. Navy ships [5]. On these same vessels, only 19 percent of the labor costs are attributed to the hull structure. Thus it appears that the primary cost driver for complex ships is outfitting.

In addition to the above stages, many components and small sub-structures are manufactured and sub-assembled by the yard itself, prior to assembly.

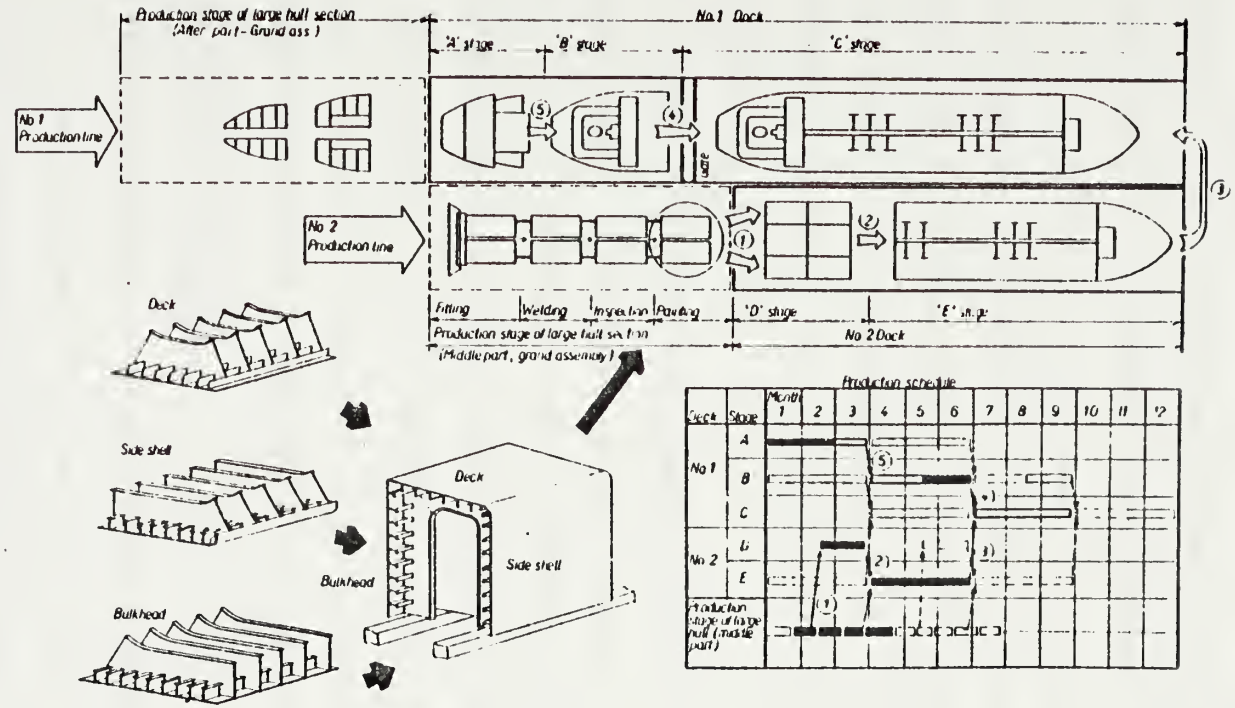
This described evolution of gneeral assembly stages is depicted in Figure 3.1. An example of a state-of-the-art ship assembly line is shown in Figure 3.2 [6]. The tanker in this example is divided into an outfit-intensive aft ship section, requiring installation of machinery, control, and habitability items, and a large forward section consisting primarily of easy-to-build tanks.

Straight and shaped panels weighing between 100 and 400 tons are assembled in fabrication shops and transported to a staying area ahead of the building docks. There, with the help of special cranes and jigs,



Evolution of Ship Assembly

FIGURE 3.1



Dual Dock Construction

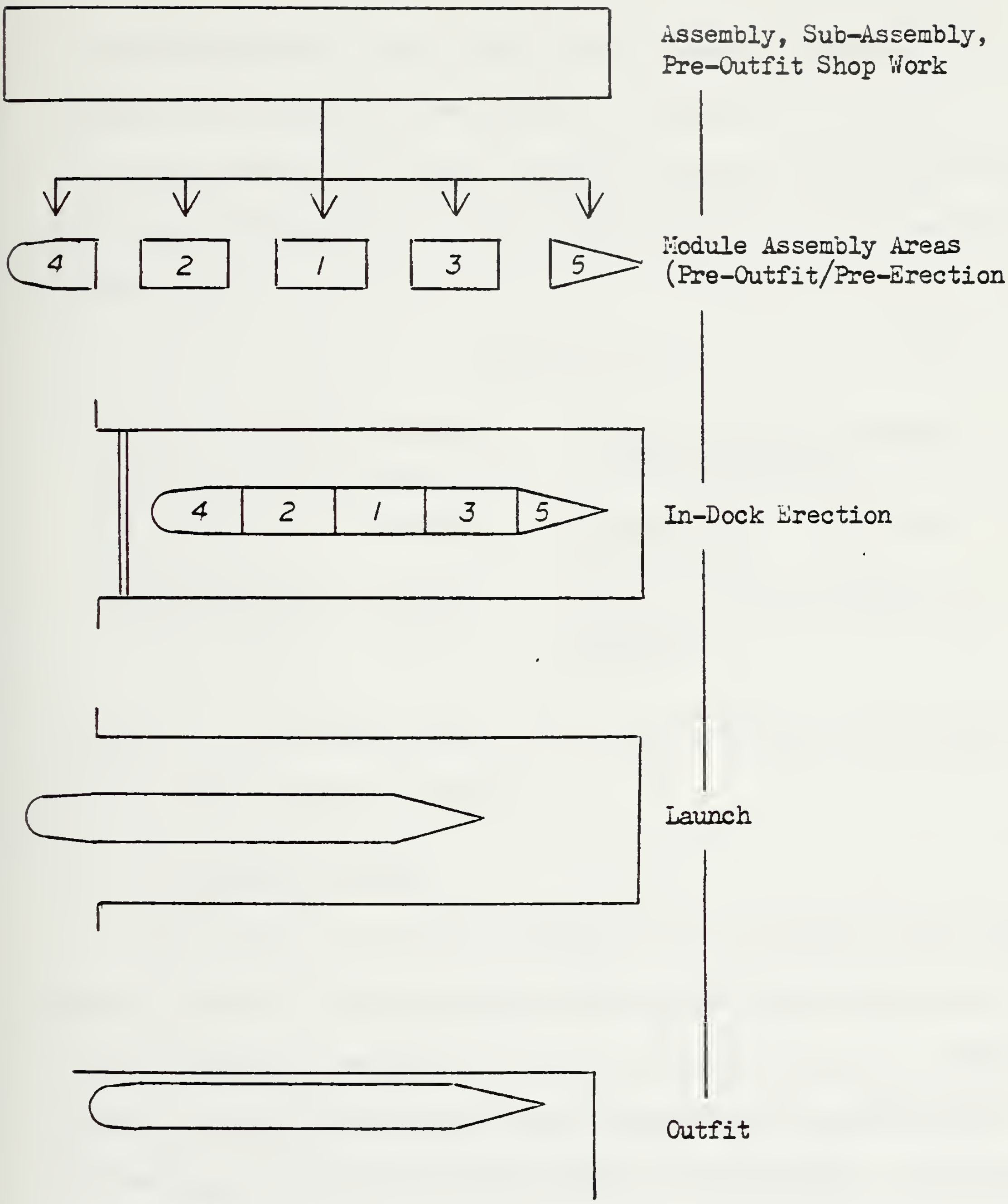
FIGURE 3.2 [6]

they are further assembled into larger three-dimensional sections weighing 700 tons. During this grand assembly, all outfit components which can be installed are completed. Continual checks on section dimensions are made during assembly and welding to prevent errors and to insure a good fitup of units during final erection in the docks. When both of the two hull sections are ready for joining, both are floated out and moved to the head of dock number 1 where this process is accomplished. The associated production schedule shows that these facilities have the ability to produce one of these 235,000 DWT tankers every three months, even though the total fabrication period for a single ship is nine months or more [6].

The above two-dock system is not readily usable to builders of outfit-intensive vessels, including complex warships. A better method for this application is to assemble and pre-outfit modules in parallel prior to in-dock module joining and final erection as shown in Figure 3.3. The rationale for this approach, in lieu of the two-dock system, is that the degree of required outfitting is more evenly distributed over the length of a warship than a merchant tanker.

3.3. Shipyard Welding Requirements

Welding is the most labor-intensive process involved in shipbuilding and accounts for some 15 percent of all merchant shipbuilding labor. This may be further broken down into structural welding (55-65 percent



Single Dock Construction

FIGURE 3.3

of welding manhours), pipe welding (18-23 percent), burning (18-15 percent), and sheet metal welding (3-7 percent) [7].

Of the structural welding required butts and fillets constitute the bulk of welded joints in the following proportions for merchant ships:

Table 3.1 [8]

Type of Joint	Proportion	Typical Welding Equipment Currently Used
Butt Joint	20-25%	Submerged arc, electrogas, electroslag
Fillet Joint	75-80%	Gravity and mechanized line welders

In order to assess the potential for robotic welding, the process needs of each stage should be assessed.

3.3.1. Subassembly Stage

Subassembly work requires welding in all positions, even though movable jigs are often employed to effect the downhand position. Use of such jigging is practical for small subassemblies only. Complex, cramped work has traditionally been accomplished by manual SMAW or semi-automatic (manually guided) GMAW and GTAW methods. All methods used are very labor intensive. Many of the fabricated pieces have extreme dimensions of 10 feet or less, such as machinery and equipment foundations. Most are unique or require only a small degree of duplication. Piece variability and low volume have precluded extensive welding automation in this application area, with the exception of structural girder and stiffener manufacture [9].

3.3.2. Assembly Stage

Much of assembly work is comprised of flat or curved panel fabrication. Fujita, et al. [8] report that 48 to 56 percent of all merchant ship welding occurs in assembly processes and assembly-stage pre-outfitting in Japanese shipyards. This high percentage reflects a commitment to widespread use of automated processes and decreasing the amounts of required building-dock work.

Most flat panels are constructed by one of three methods:

1. Individual assembly of skeletons
2. Pre-assembly of longitudinal members (Line Method)
3. Pre-assembly of frame (Eggbox Method)

As depicted in Figure 3.4, the first method, while simple, does not readily lend itself to extensive automation. The line method, most popular in Europe and the United States, employs a single mechanized production line which improves piece handling. The eggbox method uses parallel lines for frame assembly and plate butting before final joining. This system is most common among Asian shipyards.

However constructed, the majority of panel weldments is in plate-stiffener or plate-girder fillets. Vertical fillet and lap joints at stiffener-girder junctions and collar plates generally require less weldment, except in the case where structural stiffening members require high web height, such as double bottom assemblies. Plate butting is frequently minimized by cutting wide (10 feet or more) plating to prescribed panel lengths.

Welding methods used by these three methods vary depending on the level of technology employed and the experiences and practices of the

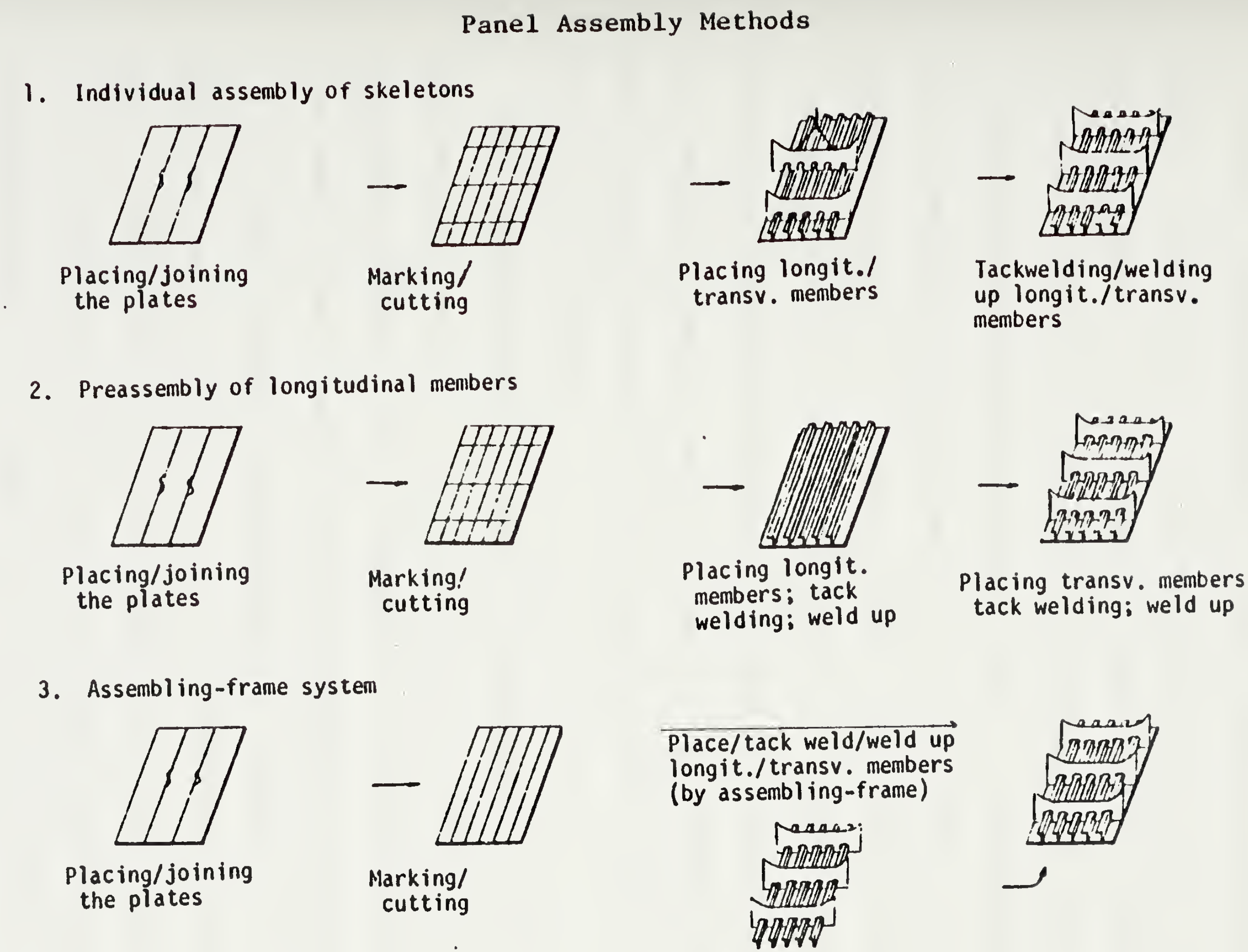

Panel Assembly Methods
1. Individual assembly of skeletons
Placing/joining the plates
Marking/ cutting
Placing longit./ transv. members
Tackwelding/welding up longit./transv. members
2. Preassembly of longitudinal members
Placing/joining the plates
Marking/ cutting
Placing longit. members; tack welding; weld up
Placing transv. members; tack welding; weld up
3. Assembling-frame system
Placing/joining the plates
Marking/ cutting
Place/tack weld/weld up longit./transv. members (by assembling-frame)

FIGURE 3.4 [8]

people who use them. The skeleton assembly method requires little automation and consequently the lowest degree of capital investment. The typical line method facility relies on mechanized stiffener handling, and mechanized welding particularly along plate butts and stiffener fillets, in conjunction with manual tacking. Significant investment is required for purchase, installation, and support services for these readily marketted production lines. A large capacity facility employing the eggbox method relies on extensive use of heavy handling machinery for stiffener, girder, and bulkhead placement and alignment. High deposition welding methods including automatic tacking machines are used wherever possible. Shipyards employing these methods have invested tremendous amounts of capital and in-house R and D to develop prototype production facilities tailored to meet that yard's particular requirements.

As a consequence of the levels of technology most often employed by these methods, they are often described as low, medium, and high technology production lines, respectively. The welding processes most often used in these assembly methods are depicted in Table 3.2.

The level of panel line technology has advanced to the state in some Asian yards to eliminate the use of collar plates for certain types of construction. This is accomplished by using giant handling jigs to slide stiffeners through closely-fit girder slots when assembling the eggbox lattice [8]. These same lines employ automatic quadruple-head, vertical fillet-welding machines to join the stiffener-girder intersections, and to significantly boost worker productivity and reduce station cycle time.

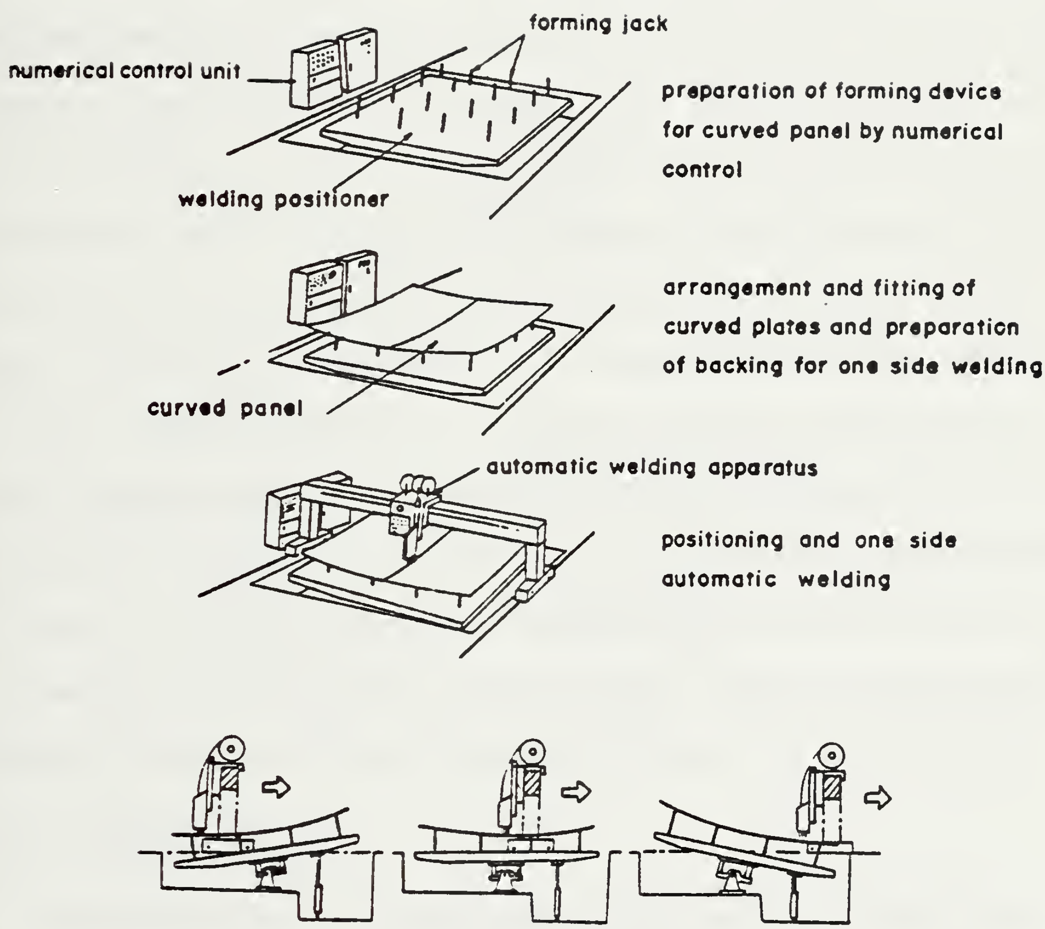
Application	Process
Butts	SAW
Stiffener to Plate	Gravity
	Automatic GMAW
	SAW Tractors
Girder to Plate	Gravity
	Semi-auto. GMAW
Stiffener to Girder	SMAW
	Semi-auto. GMAW
	Automatic GMAW
Collar Plates	SMAW
	Semi-Auto GMAW

Table 3.2. Panel Welding Processes

Curved panel assembly has much in common with flat panel assembly, but requires closer control of fitup accuracy. Panels, curved by bending machines are butt welded on pin jigs, contoured to the desired shape. Structural members can be assembled and joined to plating by any of the three flat panel assembly methods. It should be understood, however, that the complicated and difficult fitup requirements of curved panels and structural members most often requires use of individual skeleton assembly. Manual jigging and labor-intensive fitting are prevalent in the United States. Some advances have been pioneered by Japanese shipbuilders in the use of automated jigging and positioning. One device, developed by Kawasaki Heavy Industries, some 15 years ago, consists of a numerically-controlled, tilting positioning table with adjustable magnetic forming jacks as shown in Figure 3.5 [10]. The table permits the use of high-deposition, one sided submerged arc welding for plate butting when a welding gantry is suspended overhead or a welding tractor is employed. A similar tilting table is used for joining the eggbox lattice to the plating. Most of the flat-panel welding methods are used for curved-panels, but with a higher proportion of GMAW, FCAW, and SMAW applied to positions other than horizontal.

3.3.3. Block Assembly Stage

The type of welding process used in block assembly depends, to a large degree, on the sophistication of handling equipment and fitup procedures employed. New assembly systems have been developed to simplify fitup and minimize welding in elevated positions. This development has initiated a new trend in shipbuilding practice of



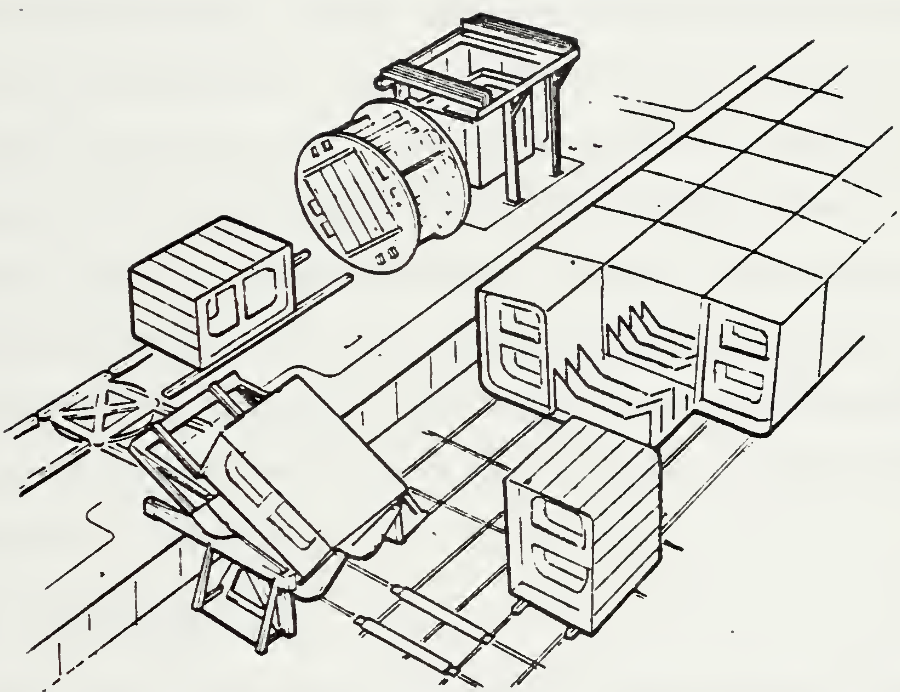
Kawasaki Curved Panel Table

FIGURE 3.5 [10]

replacing the method of joining blocks and panels with alignment referenced to the workpieces themselves, by an alternate approach by which proper fitup is ensured by the assembly frames serving as jigs. An example of this is Mitsui's ROTAS (rotating and sliding) system in which large rotary assembly jigs are employed to erect cube-shaped tank blocks of 800 to 1400 tons (see Figure 3.6). By rotating the jig, welding tractors are used to weld required seams and fillets in a flat position. Use of these jigs, however, does require compatible hull structure design. Specifically designing for such a production process can greatly enhance the utility and productivity of mechanized methods, but is not always possible in yards constructing a variety of ship types. The bulk of shipbuilders use conventional labor-intensive means of block assembly, depending on dedicated overhead crane support, manual fitting and tacking, and multi-position welding. Here, the importance of production-friendly structural design is again stressed to simplify the fitting process. Common welding methods used for joints include SAW, gravity, SMAW, GMAW, and FCAW. SMAW and semi-automatic GMAW and FCAW are used where mechanized methods are not effective.

3.3.4. Erection Stage

Erection welding at the building site requires a careful and difficult fitting procedure and a large physical range. Because support services at the dock are not as readily available as in a block assembly hall, erection joints should be made as uncomplicated as possible, but yet allow satisfactory block-fitting. The portability of welding equipment becomes important, particularly in less accessible,



ROTAS Block Assembly

FIGURE 3.6 [8]

interior joints. Consequently, a number of processes are used for different joints. Electro-gas and electro-slag are used in long vertical butt welds of side shell and longitudinal bulkheads. These methods enjoy extremely high deposition rates and a certain amount of fitup tolerance, but require significant setup time and adjustment. Manual methods and GMAW are frequently used for shorter or less accessible vertical joints. SAW is used most for longer length butts in decks and platforms. Manual methods or semi-automatic GMAW and FCAW are used frequently for short length flat and overhead butts, all short run fillets, and in hard-to-reach areas. Long side shell seams are well suited for mechanized GMAW and FCAW systems, often equipped with oscillating mechanisms. As in all cases, the sophistication of welding methods used depends on the shipyard's readiness to invest in modernization. With the trend toward more producible designs and more before-erection welding, the need to evolve erection welding methods may diminish [11].

3.3.5. Outfitting

The primary application of welding to the outfit of a ship is pipe welding. The majority of welding occurs during its manufacture, not during its outfit or preoutfit installation. In recent years, the introduction of commercially-available semi-automatic pipe welders has made shipboard pipe installation and repair simpler for those choosing to invest in their capability. Most have a flexible or rigid track surrounding the pipe to be joined with a GMAW weld head. For small pipe diameters (6 inches and below), lightweight, hand-held systems are available. All of these units have a programmable travel speed, wire

feed rate, and feed motions. Computer-controlled automatic welding machines have been developed in the past several years. These compact, lightweight units employ a microprocessor to set and control welding parameters, passes, and welding head travel.

The applicability of these systems for construction and repair purposes depends on the accessibility allowed by ship design. Where accessibility is not adequate for automated or semi-automated systems, manual methods continue and will continue to be used.

The issues pertaining to the application of welding technology to piping are not unique to the shipbuilding industry and therefore will not be discussed further.

CHAPTER 4

ROBOTIC WELDING SYSTEMS FOR SHIPBUILDING

4.1. Robotic System Design Criteria

The industrial robot, as defined by the Robot Institute of America [12], is "a programmable, multi-function manipulator, designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks." What separates an industrial robot from other types of automation is the fact that it can be reprogrammed for different applications. Hence, a robot falls under the heading of "flexible automation", as opposed to "hard", or dedicated, automation.

Industrial robots are devices that perform tasks too physically demanding, menial, or repetitive for a man to do efficiently. Industrial robots generally consist of an arm, to which an end effector (gripper, welder, drill) is affixed; a power source supplying electrical or hydraulic power; and a control unit providing direction for the robot.

Robots are classified in a number of ways, including spatial coordinate system, drive actuator, work volume, load capacity, control type and sophistication, and dynamic performance. It is beyond the scope of this paper, to pursue this subject in greater depth. However, the reader's attention is called to several references ([13], [14]) which provide good initiation to this subject.

In applying arc-welding robots to shipbuilding the following factors must be appraised [15]:

- System flexibility
- Scale requirements
- Access constraints
- Control system requirements
- Fit up adaptability

4.1.1. System Flexibility

The term "robot flexibility" needs clarification. It should be recognized that any introduction of robotic, automatic, or mechanized welding inevitably reduces overall system flexibility. This is because no robot has the intelligence or autonomy of a human. Flexibility is really a composite quality to be dissected, if understood. The ultimate goal is maintaining overall flexibility of the shipyard.

The primary measure of a robot's flexibility is its operating envelope, which is a function of its size and mobility. The specification of the required operating envelope is the major difficulty in applications of large scale assembly. If a large fixed station device is a means of welding a large range of assemblies, then overall yard flexibility may be reduced. This is because the operation is constrained to a fixed location and therefore production throughout must be carefully matched to other process-related work stations. On the other hand, a truly autonomous mobile, small welding roboy is not a realistic alternative with forseeable technology. Mobility via manual or mechanical transport involves compromizing capability and limiting use to particular applications. The fact that the robot must be brought to the workpiece, not the workpiece to the robot, is a critical difference.

Achievement of flexibility through mechanical adaptivity (or robot modularity) may be important. Assembly procedural variations may be achieved in part by manual, physical adjustments of the welding device and/or robot. Thus, limited human participation and intervention can simplify system design requirements, while maintaining improved applicability.

Another measure is the robot's ability to adapt to fitup within a particular assembly to which it is otherwise matched. This capability is, to a large degree, based on the installed sensor technology and software.

Multi-functionality is yet another measure of flexibility. As an example, a single device might both prepare a joint by grinding, and then weld it. This is not necessarily achievable, since the mechanical specifications for paired functions are often incompatible.

4.1.2. Scale Requirements

The requirements of subassemblies on the order of 100 m^3 and 40 tons and assembled panels of 600 m^3 and 75 tons are what distinguishes shipbuilding from other robotic applications. The simple upscaling of conventional industrial robots is probably not sufficient for such applications. Mobility is a more likely means of extending the operating envelope.

However, every fabricated assembly can be broken down into smaller elements, according to the complexity of weld geometry. Hewit and Love [15] have established a scale of robotic welding sophistication for large assemblies, as shown in Figure 4.1, which demonstrates the tradeoffs

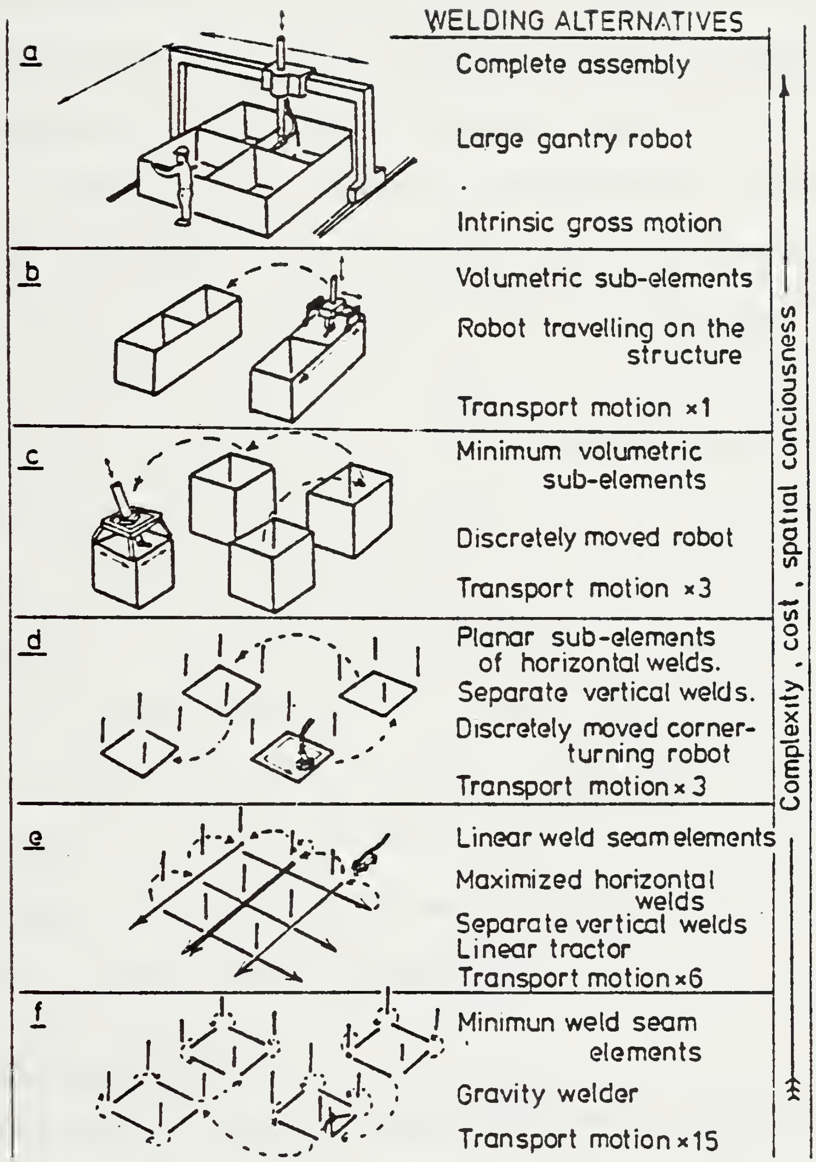

WELDING ALTERNATIVES
a
Complete assembly
Large gantry robot
Intrinsic gross motion
b
Volumetric sub-elements
Robot travelling on the structure
Transport motion ×1
c
Minimum volumetric sub-elements
Discretely moved robot
Transport motion ×3
d
Planar sub-elements of horizontal welds.
Separate vertical welds.
Discretely moved corner-turning robot
Transport motion × 3
e
Linear weld seam elements
Maximized horizontal welds
Separate vertical welds
Linear tractor
Transport motion ×6
f
Minimun weld seam elements
Gravity welder
Transport motion ×15
Complexity , cost , spatial conciousness

FIGURE 4.1 [15]

to be made between capability and cost for designing a system. As the assembly's elements become simpler, their number increases, effectively increasing and simplifying the number of repeated welding motions. As the tasks become simpler, inherent mobility decreases, requiring more human intervention. When human beings are needed for system transport, the responsibility for maintaining spatial consciousness is shifted from software to them, as well. Weld seam consciousness is, however, retained by the machine. This concept of separating transport from a long-seam motion is important. With a large single-headed gantry robot welder, the component parts of the gantry which position the robot over the assembly are inseparable from the degrees of freedom of weld motion. Thus while precision welding takes place, they are redundant. The concept of a human or automatic crane picking up and placing multiple devices allows separation of transport and eliminated redundancy.

Another distinguishing effect of large scale application is the capacity to use the assembly itself for supporting a welding robot. Welding tractors are commonly used in this way. Potential drawbacks of these systems are the increased chances of interference and entanglement with their long, heavy umbilical cables.

4.1.3. Access Constraints

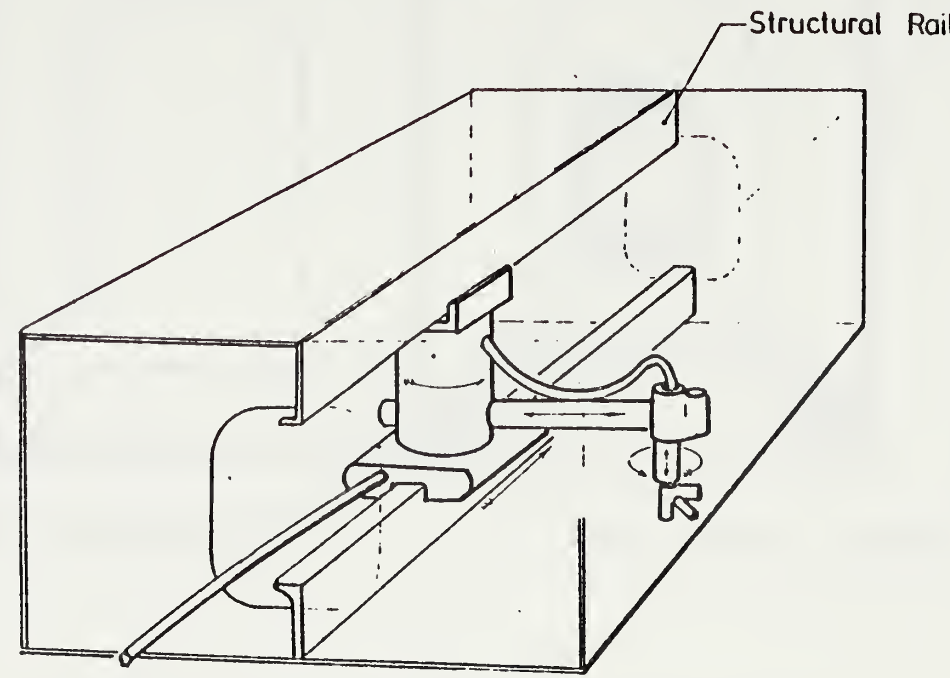
Selection of a robotic welding system becomes difficult when access to partially closed spaces is required. An example of this, often required in shipbuilding, is the construction of double bottoms. This situation can be handled by one of three means:

- use of a specialized weld head manipulator to reach through constrained accesses
- redesigning access holes to more readily accommodate or support robot welders (Figures 4.2 and 4.3)
- redesigning the ship to eliminate the requirement for a double bottom.

4.1.4. Control System Requirements

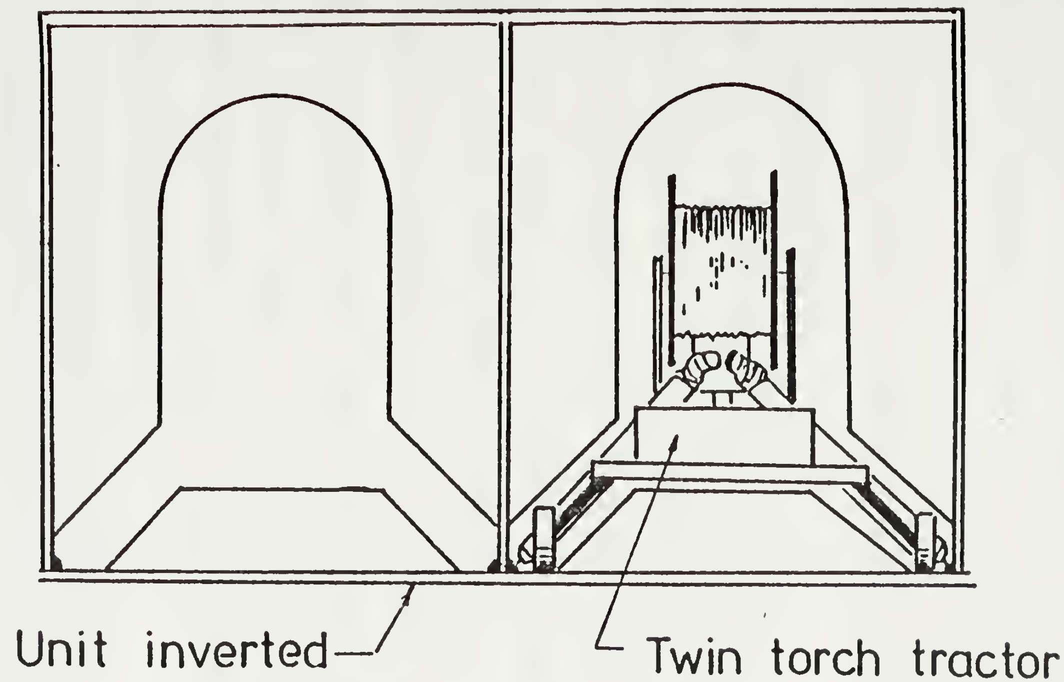
Control requirements are a function of spatial consciousness as depicted in Figure 4.1. Accordingly, the level of required human interaction must be determined, considering ergonomic and system requirements. If orthogonal structures are the usual application, rectangular cartesian robots can be used, thus simplying control software. In such cases, a single axis of control need be supplied to execute movement along a weld path. The components of feedback from seam tracking correspond with primary axes, eliminating the need for coordinate transformations [15]. Endpoint determination can be eliminated from software, if active sensors are used.

Software and processor requirements are, as expected, dependent on the sophistication of the sensing and control systems used and how the robot's assignment is tasked. Programming can be accomplished by "on-line" or "off-line" means. However, the U.S. Navy has concluded that the time required for on-line programming "could be a serious hindrance to the effective use of state-of-the-art robots in shipbuilding because of the very small batch sizes encountered" [16]. Accordingly, the Navy, at its Naval Ocean Systems Center, is working to develop and demonstrate a generic technique for controlling a complex industrial process



Concept of using the structure to provide a degree of freedom

FIGURE 4.2 [15]



Simplification of welding requirements

FIGURE 4.3 [15]

through knowledge-based techniques, analyzing and reacting to data from a number of sensors. Its first application involves integrating the components of a robot workcell for real-time adaptive control of the GMA welding process. It is expected that these efforts will produce systems to take CAD-generated designs from welding engineers or production planners and translate them into task descriptions, recognizable to robot control software. Similar efforts to provide an adaptive CAM link between CAD and robots have been described elsewhere [17], [18].

4.1.5. Fit up Adaptability

The task of joint seam tracking is complicated by weld-induced distortions in addition to the alignment and dimensioning errors expected in any large fabricated structure. Consequently, active, real-time sensors become important to providing the feedback needed to maintain control. A number of methods of seam tracking are being used or investigated for commercially available robotic welding systems including ambient light vision, structured laser vision, tactile sensing, arc-parameter sensing, acoustic sensing, and electromagnetic sensing.

These contact and non-contact sensors should ideally meet all of the following requirements: [19]

- Applicable to different weld geometries
- Applicable to different welding techniques
- Real-time operation
- Provides three-dimensional information on the seam geometry and fit up
- Able to "find" its correct starting position
- Small in size so as not to limit the motion of the arc welding torch

- Inexpensive in comparison with the total cost of the robotic system
- Reliable and rugged enough to endure a hazardous environment.

Tactile probes are attractive because of their simplicity and reliability. However, information on joint fit up is difficult, if not impossible, to acquire. Certain geometries, including concave corners, preclude the use of these sensors.

The majority of current research in seam tracking appears to be in the area of computer vision systems. Low light-level television and projected, structured light have been combined for real-time tracking for submerged arc welding [20].

Exposed arc processes such as GTAW and GMAW require the use of structured laser light to eliminate weld arc interference. The vision system being developed at SRI International [21] operates by scanning the workpiece with a point source of light that is directed from a solid-state GaAs laser through a collimating lens and a series of steering and scanning mirrors. The reflected light is directed to a linear diode array, with each mirror scan providing a two-dimensional slice of the workpiece surface. Multiple scans provide the aggregate data for constructing a 3-D image of the workpiece surface. This system's drawbacks stem from its present high cost and significant computational requirements for image processing.

A completely different approach to seam tracking is to use the voltage or current characteristics of the arc itself. These techniques are generally referred to as 'through the arc' sensing systems. A small oscillatory motion of the arc results in a corresponding change of

the current or voltage. This measurement can be converted into positional information of the torch,relative to the joint. These systems suffer from the fact that they are not capable of determining the starting position of the welding torch. Furthermore, the technique is not applicable to sheet metal welding.

Acoustic and electromagnetic sensing systems may offer some advantages over other non-tactile sensors, but research emphasis appears to be directed in other sensor areas. The reader is directed to reference [19] for more information.

Some discussion has been raised [15] about the need for joint gap sensing. Opponents of gap sensing cite improved joint design and quality control, coupled with slightly overspecified weld dimensions, as the means of eliminating the estimated 5 percent of unacceptable ship fillet joints. However such a strategy limits the potential utility of robotic systems to actively optimize weld bead dimension and perform real-time in-process quality control. Furthermore a system lacking gap sensing would be unable to detect unacceptable weld-induced distortion. It is therefore believed that gap sensing is still an important capability for large scale shipyard welding robots.

4.2. Welding Subsystems

A number of welding processes are used in conjunction with robotics in industrial applications including, GMAW, GTAW, SAW, and plasma welding. Of these, GMA welding appears to be the most popular [22], due to its comparatively good deposition rate, multi-position capability and low relative cost [9]. The use of submerged arc welding has mainly

been directed to long-run flat applications, where mechanized welding is cheap and efficient, not the primary domain of labor-saving robots. GTAW-robot systems have been applied primarily to small-scale light-gauge fabrication and are not as advantageous for most shipbuilding applications.

Another area of robotic welding research being pursued by the U.S. Navy is lasers. The inherent advantages of laser welding as a process requiring lower heat input and producing a narrowed heat affected zone are offset by guidance problems [23]. The small welding spot diameter (.040 in.) of this method requires tracking accuracies within .005 inches to insure the beam hits both pieces being welded. Beam drift caused by mirror misalignment, mirror heating, rising temperatures, atmospheric pressure variations and robot misalignment will require a seam tracking capability at least an order of magnitude more accurate than required by other welding processes. Therefore it is predicted that robotic laser welding will be seen in shipyard applications, only after conventional robotic processes have been widely accepted.

Gas metal arc welding processes used for robotics may vary in the future. All three variations of GMAW, namely MIG (metal-inert-gas), MAG (metal-active-gas) and FCAW (flux-core arc welding), are currently used by robot welders in industrial applications. However, most robot GMA welding has been accomplished with filler wires normally sized for semi-automatic (manually guided) welding, specifically 1/16 inch (1.6 mm) diameter or less. Hence, spray transfer, flat position deposition rates have been limited to about 13 to 16 lb/hr, depending on wire type and amperage. The large diameter (up to 4 mm) GMAW wires used in mechanized

welding have deposition rates up to about 20 lb/hr [24]. In Japan, the use of 2 or even 3 wire, single-pass GMA welding is not uncommon for horizontal and vertical butts in large-scale steel fabrication [25] [26]. It may be possible to apply a multiple wire GMA welder to different positions in fabrications of lesser thickness, if heat input can be satisfactorily controlled to produce acceptable distortion and metallurgical properties. Such a scheme would allow both higher arc speeds and faster production rates, essentially by converting from single-head, multi-pass welding to multiple-head, single-pass welding. This operation would probably require a complex, adaptive, closed-loop feedback system, including seam/gap sensing, to provide the necessary controllability of wire oscillation and conventional GMA welding parameters for multi-position production welding. The robot's ability to move an end effector at fast, precise speeds along a programmed path could provide the required locomotion for this multi-purpose, multi-headed system. Such an advance in welding technology could increase production rates (arc speed and deposition rate) so that the rate capability of the entire system would be limited by its guidance and process control computation requirements.

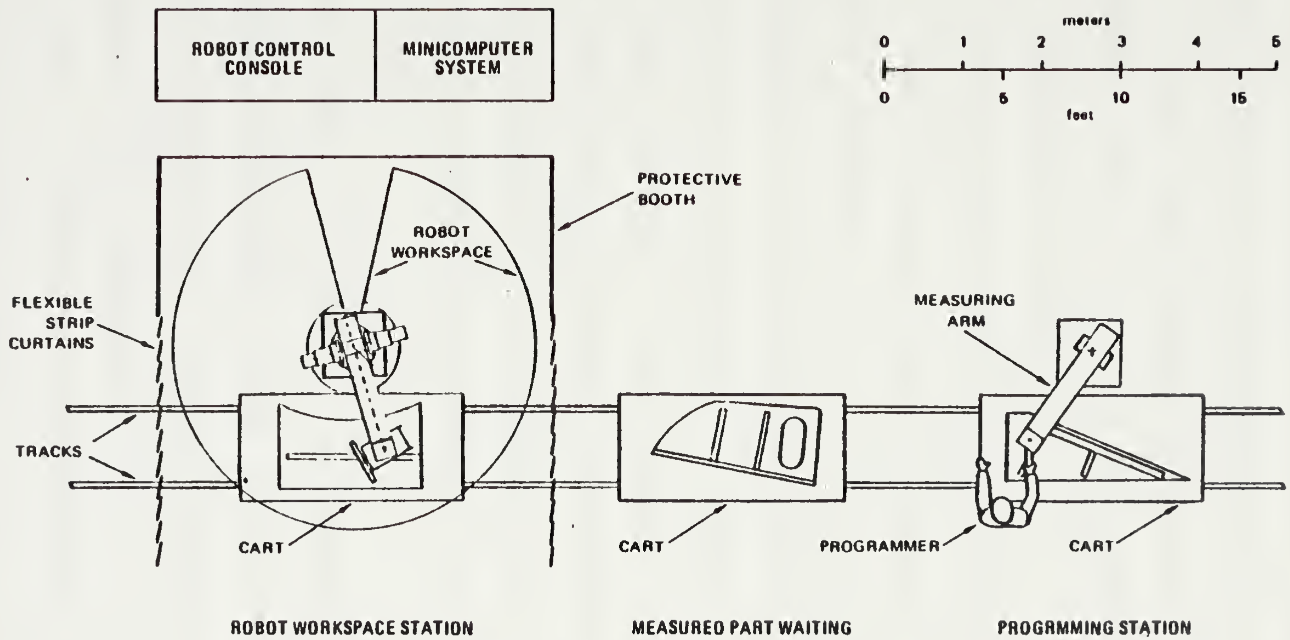
The point to be made is that future developments in welding processes will likely improve productivity with or without robot guidance. However, a sophisticated adaptive process control capability will be required to effect some of these advances, whether they be applied to robotic or other types of automated welding.

4.3. Proposed Concepts

A number of robotic arc welding concepts have been developed for potential use in shipyards. Some of the prototype systems have fared well in field tests, while others have proved disappointing.

The most promising applications of robotic arc welding appear to be small scale subassembly fabrication where the technology for implementation already exists and economic incentives appear satisfactory for continued development. The ongoing project conducted by Todd Pacific Shipyards and SRI International [21] for the Navy is developing a prototype robotic arc welding work station for this purpose. Employing a Cincinnati-Malacron T3 industrial robot, with a Hobart flux-core GMA welding system, Aronson dual positioner, and associated support and visual seam-tracking equipment, this system has performed well in operational tests thus far. The good flexibility of this stationary system should allow a sufficient number of small-batch ship parts to be fabricated to economically justify introduction of a derivative production system. Such a system will use either a CAD/CAM data base or a preprogramming station with lightweight measuring arm (teaching device) as illustrated in Figure 4.4 to effect offline programming.

Applications in the area of assembly may also be promising. Because of the large size and weight of ship panels, welding robots are required to be mobile within their work envelope. These panels are normally fabricated on some sort of factory line; thus welding robots would have to be integrated with existing man-machine systems to insure comparible output rates and smooth overall production flow.



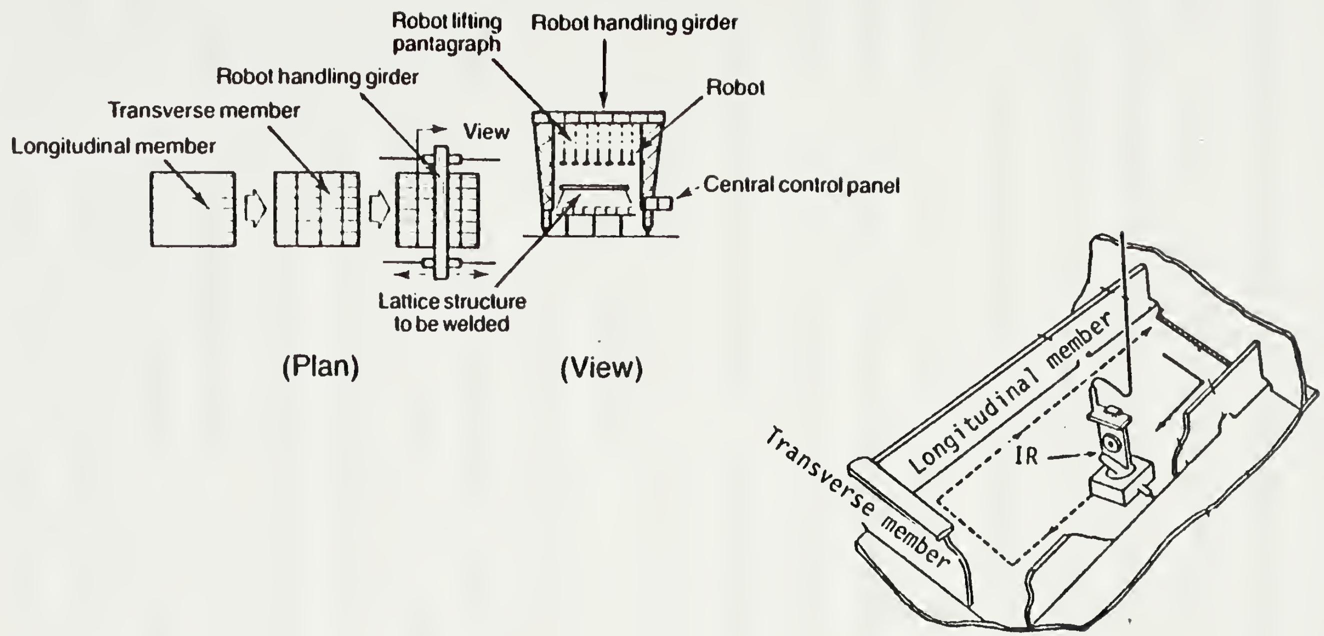
USING A MEASURING ARM TO PROGRAM A ROBOT

FIGURE 4.4 [21]

Most assembly line concepts accommodate the mobility requirements by providing the robot with a movable gantry that straddles the work area or with some form of self-locomotion to physically crawl along the assembly. These concepts were developed specifically for the joining of girders and in some cases stiffeners to flat plating. Consequently they would primarily produce single-pass fillet welds in the horizontal and, for some, the vertical positions.

Precedence for the gantry-mounted welding robots already exists in the numerically controlled gantry fillet welders used for panel assembly in a couple of U.S. shipyards [27]. However these custom-built systems have limited flexibility and limited gantry span to prevent weld path errors induced by structural deflections. It is anticipated that adaptive seam-tracking would compensate for this problem in larger gantry robot systems. This concept could conceivable provide for increased productivity by mounting a second manipulator arm and weld head on the robot to perform double-fillet welding on both sides of the stiffener or girder, simultaneously [28].

The crawling robot, not dissimilar from mechanized welding tractors, would allow integrated production welding of both stiffeners and girders to plating but not have a vertical welding capability. Fujita [8] has described a lattice fillet welding robot tractor to be used for eggbox-method panel assembly. The entire system consists of individual robots tasked to fillet weld assigned structure lattices, and a handling gantry that repositions the robots over the structure as depicted in Figure 4.5. It is assumed that these robot tractors will have adaptive positioning and seam-tracking capabilities. While this system lacks



Lattice Fillet Welding Robot Concept

FIGURE 4.5[8]

the vertical welding capability of the gantry concept, it will also lack the technical complexities required for positioning and controlling the welding process in that third dimension.

While promise of technical feasibility exists for assembly applications, the outlook for robotic arc welding in erection work does not appear to be good. Firstly, the evolution of shipbuilding methods is shifting more and more welding work from erection to pre-erection stages. Secondly, the mobility requirement must be compounded to allow maneuvering inside odd shaped compartments, climbing over ribs and bulkheads, and scaling the sides of the ship's hull. These problems are further compounded by the lack of a controlled environment in which the robot would operate, subject to weather and interference from collateral work. The extreme requirements for maneuverability call for compact, lightweight systems; yet they must provide for the handling of welding and power cables over long distances.

Early attempts at erection application welding robots have not been successful. The CLIMACS ship hull climbling robot described by Kihara [29] as a platform for mounting robots, climbs up the ship's side longitudinals with four chucking and pushing mechanisms corresponding to arms and legs. It was found to be too large,clumsy,and heavy to safely climb the hulls of ships with scantlings smaller than those of large tankers. This concept was apparently abandoned. More recently Unimation's "Apprentice" welding robot, designed for portable, multi-position welding in remote erection areas, was determined to lack sufficient capability and reliability for production welding in any shipyard applications [30].

It is believed that these early failures are indicative of the extreme technical challenges facing robot designers in ship erection applications. Furthermore, robot systems would have to compete with existing automatic and mechanized erection welding methods, and the improvements to their productivities with technological advances. Adaptive seam-tracking and weld control, by "thru-the-arc" methods, are already commercially available in tracked automated GMA welders used in erection operatations [31]. Thus the inherent technical risk of these robotic research efforts, coupled with a limited potential for economic payoff, due to the competition among technologies and the relatively small domestic shipbuilding market, will likely discourage significant progress in this area of shipbuilding application.

4.4. Social Impacts

An issue of concern with many in labor, industry and government is the human resource impact of the robotics "revolution". However, much of the public awareness of robots has been shaped by the hyperbole in the popular press in recent years, since very little hard data exists on their social science aspects. Despite the limited availability of good information, the potential impact of robotics on the ways in which we lead our lives is sufficient to warrant closer examination of these issues. Of particular pertinence to the subject of this thesis are the issues of required skills and training,job displacement, man-machine interaction, and, perhaps most importantly, human resource management and industrial relations.

4.4.1. Skill Level Requirements

The application of robotics to manufacturing has long been touted as a means of improving the quality of working life by making difficult or fatiguing work easier and hazardous work safer. Consequently it has been assumed that robots would allow less skilled workers to produce goods formerly requiring workers to possess more training and inherent manual ability. Indeed a number of studies [32] have shown this predicted result to hold true. For the case of a totally unmanned production system, the manual skill requirement declines to nil. While blue-collar manual skill has, in fact, decreased in robotic production system, so have inherent management or decision skills. Even on the most tayloristic shop floor, this skill was needed to handle the multiple variances in product, quality, and pace that occur daily. The robotic systems have apparently caused the centralization of decision-making in the foreman's hands. This is because he has become the only person with sufficient knowledge and authority to intervene with the system's operation (i.e., stopping the system, summoning maintenance teams, etc.). The foreman has total control over the variances, both in the working process and in output in the most highly-sophisticated cases [32]. Thus it is probable that the introduction of robotics can lead to reduced skill requirements for labor and increased requirements for supervisors.

When this situation promotes humanization of the workplace and improved job satisfaction for the worker, there should be no polarization of labor-management interests. However, if blue-collar work is dehumanized by the increased disparity of worker-supervisor skill requirements and the resulting disparity of potential for job satisfaction,

conflict can erupt. This effect of dehumanization and polarization has been reported in West German industry [33] for applications of robotic arc welding. The central problem has been residual jobs associated with arc welding and their distribution. For example, when a robot is used for arc welding, the residual jobs may include manual rewelding, visual inspection, or, in the event of a robot failure, manual welding of the whole workpiece. All of these jobs still demand the skill of a qualified welder. The residual jobs that are thus created also include new, partial functions requiring low skills, for example clamping or unclamping the workpieces or "supervising" the machines (switching on or off). When these tasks are performed by a qualified welder, it is the equivalent of a demotion. Thus the situation can arise where required overall worker skill decreases, but required worker training support remains the same, leading to decreased job satisfaction.

In the future, a major task of management will be to reorganize work such that residual jobs are combined to produce positions with higher qualification requirements (e.g., shifting simple programming functions to the floor of the production line). This may have to be accomplished by shifting some supervisor skills to the worker. While reducing the disparity of skill requirements, such action would have to be carefully implemented to limit detrimental effects to supervisor motivation. Union cooperation will also be required to liberalize existing rules that establish skill boundaries and job content.

4.4.2. Job Displacement

While virtually all prognosticators have projected direct reductions in production labor for industries utilizing robotics, estimates of job creation have varied widely, and are mostly based on conjecture. Consequently, the net effect of robotic manufacture on employment levels has been difficult to assess.

In response to this issue, the State of Michigan commissioned a 1982 macroeconomic study to project changes in industrial human resource needs brought about by the introduction of robotics [34]. This study estimated that between 13,500 and 24,000 jobs would be eliminated by robots by 1990. The majority (10,500 to 18,000) will be in automobile manufacture, that state'spredominant industry. While the aggregate displacement rate for the auto industry ranged from 2.6 to 4.3 percent of total employment, the range jumped to 5.1 to 8.6 percent of total direct labor employment. These rates of worker displacement were considered significant, even over the span of a decade.

When these estimates were broken down along craft lines, it was suggested that between 15 and 20 percent of the welders and between 30 and 40 percent of the production painters in that industry, would be displaced by robots by 1990. In response to this job shrinkage, labor contracts between the auto manufacturers and the United Auto Workers have provided adequate job security and retraining assurances to prevent any substantial number of auto workers to be thrown out of work due to robot application. Any unemployment impact is likely to be felt by the labor market entrants who will find more and more factory gates closed to the new employee. Therefore, an increase in unemployment, as a result

of the spread of robot technology, will fall on the shoulders of the less-experienced, less well educated part of the labor force.

If welders in the U.S. shipbuilding industry are threatened by similar projections of job displacement, their unions are likely to demand similar guarantees of lateral transfer and retraining to provide adequate job security. The costs of these efforts will be significant. (General Motors has already agreed to a retraining effort approximating $120 million annually.) The failure of management to provide such assurances will undoubtedly lead to significant protest and unrest among shipyard trade unions.

When the issue of job creation was addressed in Michigan, researchers were surprised to find that slightly over two-thirds of the workers in robot manufacturing are in traditional white-collar areas of professional, technical, administrative, sales, and clerical workers. Only one-third are in the traditional blue-collar areas of skilled craft workers, production operatives and laborers. This phenomenon is explained, to some extent, that it reflects a young, high-technology industry with low sales, where the firms tend to be assemblers with little fabrication of parts. However, it is also indicative of a product that cannot be sold like a loaf of bread; there are significant requirements for engineering design, programming and installation for <u>each</u> specific application.

The estimate of jobs directly created by the introduction of robotics in Michigan, numbered 5,000 to 18,000. Four broad areas of industry were identified for these additions: robot manufacturers, direct suppliers to robot manufacturers, robot systems engineering, and corporate robot users (autos and all other manufacturing), as illustrated in Table 4.1. The jobs among corporate robot users identify maintenance requirements for

Potential Cumulative Direct Job Creation in Michigan Due to Robotics, 1990

Area or industry	Employment range of estimate	
	Low	High
Robot manufacturing	1,740	6,960
Direct suppliers to robot manufacturers	974	3,898
Robot systems engineering	1,059	4,238
Autos	1,065	1,776
All other manufacturing	287	865
Total	5,125	17,737

TABLE 4.1 [34]

robots, while the jobs in robot systems engineering identify the applications engineering requirements for robot systems, without regard to industry of employment.

The real meaning of the so-called robotics revolution will be the challenges presented to state and national policy makers by the inevitable displacement of semi-skilled and unskilled jobs and by their partial replacement by jobs requiring significant technical background. Manufacturing industry will likely pay for some of the predicted social costs by investing more training monies for new job skills and displacement-related transfers and by subsidizing the existing labor-base to placate union demands for job security. There are no reasons to expect the U.S. shipbuilding industry and its unions to face issues that significantly conflict with those just addressed.

4.4.3. Training Needs

It is anticipated that the introduction of robotic arc welding would not significantly reduce a shipyard's training costs. It has already been pointed out that robot operators or supervisors would require full welder qualifications to insure proper conditions for robot welding, and to perform manual rework and production work during robot downtimes. Training specialists would have to develop new programs to train welders and supervisors in the area of robot operation and maintenance technicians in robot repair.

The QA manager of one American shipyard has expressed his concern about the reduction of corporate welding knowledge and skill that might occur if robot arc welders were introduced. He has argued that robot usage would cause atrophication of the welder's process skills and,

more importantly, his ability to analyze and troubleshoot rejected and failed weldments. No research evidence exists to back this assertion, but the issue is sufficiently important to warrant further investigation.

4.4.4. Man-Machine Interaction

The cohabitation of the workplace by robots and humans will likely challenge the abilities of robot designers, industrial engineers, and industrial relations specialists. Likely to be at the core of many issues are the potential hazards to humans associated with robots, both physical and psychological.

The fast motion of large, heavy robot manipulators, in addition to the dangers normally associated with heavy electrical and hydraulic equipment effectively preclude the use of most robots in the close proximity of human workers. The best method of protecting the robot supervisor is to keep him away from the operating envelope of the robot at all times. A method called the docking-facility concept is commonly used with stationary arc welding robots employed in small subassembly and parts manufacture [14]. Employing a rotating, double-workpiece positioner, the operator sets up a workpiece for welding outside the robot's operating envelope. The positioner rotates 180 degrees and places the workpiece within the robot's envelope to begin welding. The operator in the meantime removes an already completed workpiece and sets up another to be welded. The positioner table lies between the worker and robot to reduce chance of injury in case the manipulator should throw something. Non-stationary robots will require intrusion monitoring systems for workplace applications, where human access cannot be strictly controlled. This function can be combined, in part, with collision

avoidance, which has grown from a need to protect the integrity of the robot and its end effector. A passive 3-D vision system is being investigated by the U.S. Navy for rough end effector positioning and collision avoidance, covering the entire robot working envelope [16]. It is believed that such devices coupled with deadman switches or handily placed panic buttons could provide an adequate level of safety to permit robot-human cohabitation of a large scale operating envelope.

Another issue of man-machine interaction has to do with the control of workpace. The output rate of a simple single-channel production line is essentially the output rate of its single slowest component process. If this process is selected for robotization and its output rate is increased, such that another, human-operated process becomes the slowest component process, a situation will exist that increases the required work output rate of at least one human being, to achieve the full production capability of the line. In this manner the robot essentially paces the work of the human worker on the line, causing him psychological and possibly physical stress. This situation will quite expectedly lead to a reduced quality of working life. Such deleterious use of robotics has been reported widely in Italian industries employing robots [32]. This practice should be avoided for the sake of human welfare and if labor grievances are to be avoided. It is believed that such practice in the ship assembly lines of this country could very likely stir up considerable labor unrest.

4.4.5. Industrial Relations Impact

The preceding issues have all outlined potential pitfalls to the successful long term introduction of robotics in the workplace. It is believed that an object lesson in participative and humanistic labor practices can be made by tracing Japan's successes in robot production and installation.

Japanese labor practices in major corporations which, as already mentioned, provide guaranteed lifetime employment and large biannual bonuses based on company profitability, inextricably bind the welfare of the worker with the welfare of the firm. Furthermore, the Japanese union is not based on crafts, skills, or occupations: the union is on a company-wide basis and covers all members of the bargaining unit. Employees identify with the company, not with a skill and are periodically shifted from one job to another within the company. The worker, not fearing loss of employment, has no compulsion to fear automation. In fact, as automated production generally enhances quality and profit and consequently bonuses, most employees welcome the robots. In Japan, the company assumes all responsibility for retraining employees displaced by robots. Not fearing the loss of trained workers, companies are encouraged to devote significant effort to training programs. Employees, displaced from unhealthy or repetitive tasks by robots, generally have moved to more intellectually challenging and less physically demanding jobs.

The practive of QC circles to foster employee participation in problem solving, have often been involved in introducing robots to plants. Several studies have also indicated [35] strong union participation

in introduction efforts. An apparent correlation of companies having strong QC circle activity and leadership in robotization is of no real surprise. Of course, the relatively high rate of economic growth in Japan, with its consequent demand for increased labor, has more than compensated for the losses of jobs resulting from increasing productivity, automation, and robot introduction. Some Japanese economists, however, are warning that saturation by industrial robots might create unemployment problems in the 1990's.

The concensus among Japanese industrialists is that they have displaced the U.S. as the world's leader in robot production as a result of their labor practices [35]. In American and Western Europe, the issues of robot introduction are frequently debated between labor and management, focusing on unemployment problems. This is rarely discussed in Japan and instead the positive effects are discussed: improvement of quality, productivity, and safety for employees. Stress is placed on the opportunities for higher level employment and for new industries made possible by robots. Unlike Japan, few U.S. companies have accepted the responsibility for retraining workers displaced by robots. Furthermore, the American worker does not directly benefit from the increased savings and profit created by robotics, as does his Japanese counterpart.

It is believed that the adoption of some of these described labor practices by American industry could do much to improve the likelihood of successful robot implementation.

CHAPTER 5

SHIPBUILDING APPLICATIONS OF ROBOTIC WELDING

The preceding chapter exposed a number of potential areas for application of robotic welding. The survey of available, current literature seemed to indicate greater prospects of economic and technical feasibility for subassembly and assembly stages of the hull construction process, than for the erection stage.

Before proceeding, it occurred to the investigator that means of justifying robotic welding, other than cost criteria, might exist. Consequently the notion of using robotics to expand the range of current welding applications was considered. Or in other words, special future applications of shipyard fabrication welding were sought for rationalizing robot use.

5.1. Candidate Shipbuilding Applications for Economic Justification

Based on the status of current research, it was apparent that efforts are progressing well for developing successful robotic arc welding stations for structural subassemblies [16]. The potential for robotic welding appeared that it might be good, but the area has had relatively limited exploration. Shop or pre-erection applications were not considered due to the perception that they had many aspects, in common with erection work, to discourage success. Consequently, three areas of assembly stage work were given consideration: flat panels, curved panels, and double bottoms.

Double bottom assembly was eliminated for consideration since the area is being explored by Hewit and Love [15]. Furthermore, a relatively

lesser proportion of ship construction in the United States require double hulls, due to the large amount of naval construction performed.

Curved panel assembly constitutes a significant portion of any ship's structure. However, naval architects are more frequently designing shipsto reduce the amount of curved panel work, as a means of reducing construction cost. Furthermore, the amount of required curved panel work is, to a large part, a function of the vessel's mission, displacement, and speed, and can vary significantly from hull to hull.

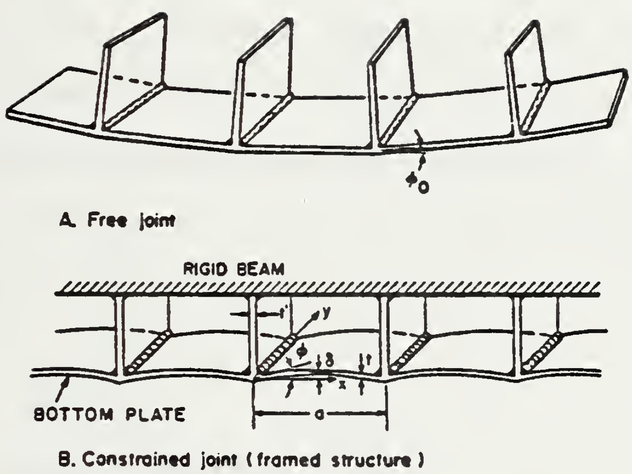
Flat panel assembly is cost preferable, and is generally well utilized among ship types. Modern barges, tankers, and bulk carriers are examples of ships designed to profit from maximum use of such economical assembly. It is believed that investigation of this area would be a worthwhile endeavor.

5.2. Special Applications

Another potential means of rationalizing the application of robotics is technical justification. In other words, do processes exist which robots can accomplish significantly better than humans? Or are there processes yet to be developed for robot use, which humans are not capable of accomplishing?

At least one such application has been identified for robotic arc welding in ship fabrication: stiffened thin-plate panel structures. As mentioned previously, panel assembly comprises a very large portion of all hull assembly work. During the Falkland Islands crisis of 1982 several of the aluminum superstructures of the Royal Navy's ship proved particularly vulnerable to shrapnel penetration and shipboard fire. As a result of these lessons, the navies of the United States and the United Kingdom are committed to designing new classes of ships with steel superstructures. To compensate for this new requirement, research efforts are being undertaken by the U.S. Navy to reduce ship structural weight by using novel structure designs and materials with high strength/weight ratios. The most promising of these is the use of thin-plate HSLA and HY-80 steel construction for superstructures and selected primary structural bulkheads and platforms.

In welding thin stiffened panels, two types of distortion are of interest to designers: arc-form (angular) distortion and buckling distortion due to fillet welds. Figure 5.1 shows the typical out-of-plane arc-form distortion found in two types of fillet welded structures. This distortion for a given amount of weld is largest when the plate



Arc-Form Distortion in Fillet Welded Structures

FIGURE 5.1 [36]

thickness is about 3/8 inch as shown by Masubuchi [36]. When the plate is thicker than 3/8 inch, the angular change decreases as the rigidity of the plate increases. However, when the plate thickness is less than 3/8 inch, the angular change decreases because the temperature differential between the top and the bottom surfaces decreases. In other words, the bending moment decreases as the plate thickness decreases.

In the case of thin stiffened panels, we are concerned with 1/4 inch thick plating or less. Consequently, angular arc-form distortion is of less concern than is buckling distortion. This is due to the formation of residual stresses caused by fillet welding stiffners to plate as depicted in Figure 5.2 . The stress field for uniaxial inplane loading has been approximated by Becker and Calao [37] and Masubuchi as in Figure 5.3. The force balance for this stress field yields the relation:

$$\sigma_r/\sigma_{cy} = (b/c-1)^{-1} \qquad (1)$$

where σ_r = residual compressive stress

σ_{cy} = compressive yield stress magnitude of material

b = plate span

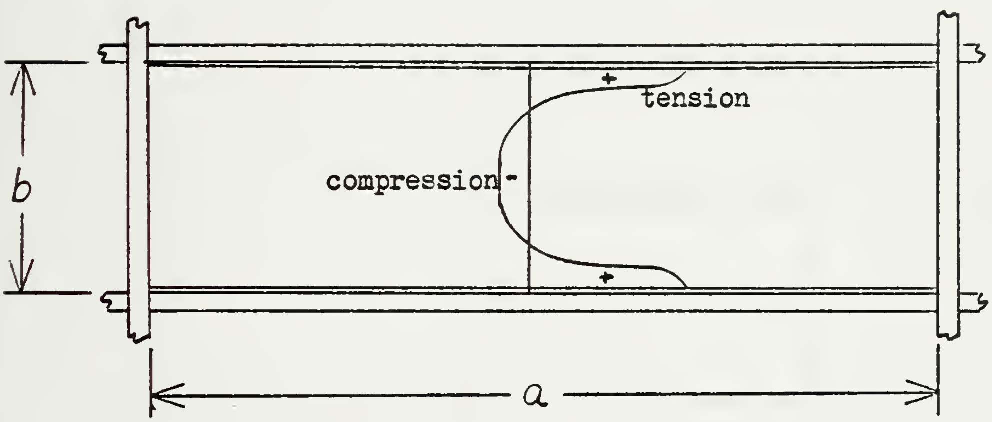
$c/2$ = effective width of weld tension stress region

Satoh [38] determined the width of the weld tension region for bead-on-plate welds to be

$$c/2 = 1.16 \times 10^{-3}\ Q/t \qquad (2)$$

where Q = heat input/weld length

t = plate thickness



Residual Stress Field of Plating Between Stiffeners

FIGURE 5.2 .

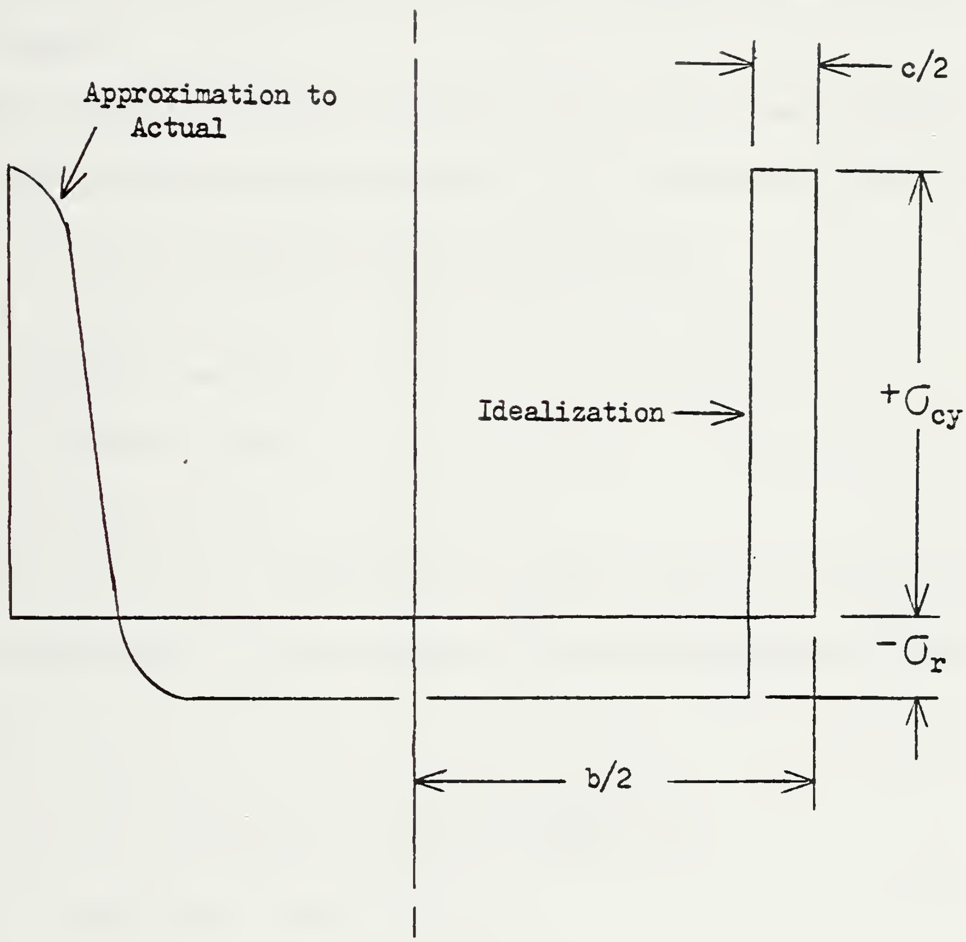

c/2
Approximation to
Actual
Idealization
$+\sigma_{cy}$
$-\sigma_r$
b/2

FIGURE 5.3 [37]

This value of c/2 can actually range from zero for an annealed laboratory test plate to a magnitude as great as 7 or 8 times the thickness, t, depending on welding procedure.

If buckling is initiated, the plate can deform to one of many stable shapes.

The solution of critical buckling stress for a simply supported rectangular plate uniformly compressed in one direction is well known as:

$$\sigma = [E\pi^2/12(1-\nu^2)][t/b]^2[m(b/a)+(1/m)(a/b)]^2 \qquad (3)$$

where E = Young's modulus

ν = Poisson's ratio

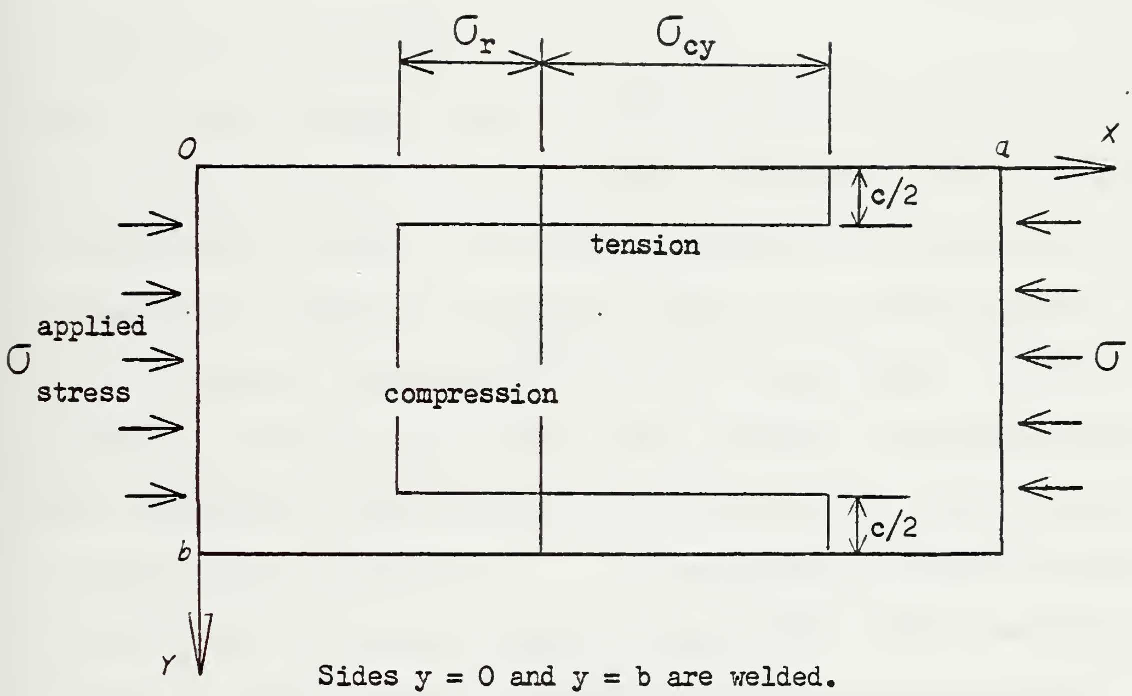
m = selected mode

Where two edges of the plate are welded, such that the residual stress distribution is as in Figure 5.4 the critical applied stress becomes:

$$\sigma = [E\pi^2/12(1-\nu^2)][t/b]^2[m(b/a) + \frac{1}{m}(a/b)^2] -$$

$$[(\sin(\pi c/b))/(\pi(b-c)/b)]\sigma_{cy} \qquad (4)$$

Thus the residual welding stresses degrade the ability of the plate to withstand compressive loading. The simply supported plate model appears to be a satisfactory one for stiffened panels as long as a/b is greater than 2 [39]. The ratio a/b for ship applications of interest are typically 4 or more for longitudinally stiffened primary ship structure. Plate panels are actually subjected to combination in-plane loads of bending, multi-axial compression, and shear, and surface traction loads



Sides y = 0 and y = b are welded.

FIGURE 5.4 [36]

with components normal to the plate. Thus an infinite number of load combinations can initiate plate buckling. Nevertheless, the preceding uniaxial analysis is useful in determining the relative magnitude of degradation caused by welding stresses.

Terai [36] found that the residual stresses initiated buckling in mild steel plates when

$$Qb/t^3 \geq 4\text{x}10^5 \ \text{cal/cm}^3 \qquad (5)$$

Thus for a given stiffener span, the heat input must be reduced by a power of three to compensate any decrease in thickness. His findings for GTA-welded plates (Figure 5.5) demonstrate that once buckling occurs, the magnitude of deflection increases rapidly with incremental heat input.

In the case of high strength alloys, one would expect increased degradation of buckling load, since those materials have significantly higher compressive yield stresses than do mild steels. This expectation is consistent with Equation (4). It is confirmed by Becker and Calao [37] who compared the value of span/thickness which induced buckling in specimens of equal thickness and equal width of weld tension region (heat-affected zone). Their findings are summarized in Table 5.1.

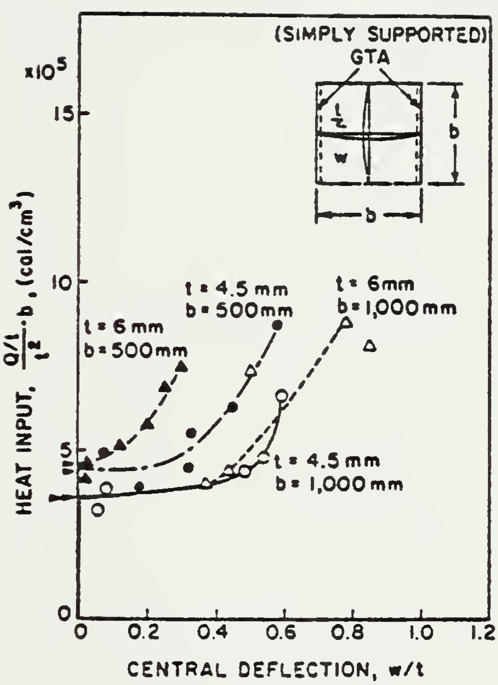
It should be recognized that since the heat input/weld length depends approximately on the volume of weld material deposited

$$Q = kl^2 \qquad (6)$$

where l = weld leg dimension

k = constant dependent on fillet welding process.

Thus positive variations in weld leg dimension significantly increase heat input.



Relationship Between Deflection and Qb/t^3

FIGURE 5.5 [36]

Material	σ_{cy} (ksi)	b/t for c/2t=3.5	b/t for c/2t=7.0
1010 Steel	39.2	378	177
4130 Steel	98.6	148	59

Table 5.1. Relation Between Compressive Yield Stress and b/t for Weld-Induced Buckling[37]

The rules of some classification societies and the U.S. Navy stipulate the minimum fillet leg dimension to be approximately equal to the thickness of the thin plate. This general guideline assumes a required joint efficiency of 100 percent in the case of U.S. Navy specifications. If the required joint efficiency is less than 100 percent some reduction in fillet size may be allowed as shown in Figure 5.6.

Additional requirements by the U.S. Navy are as follows:[40]

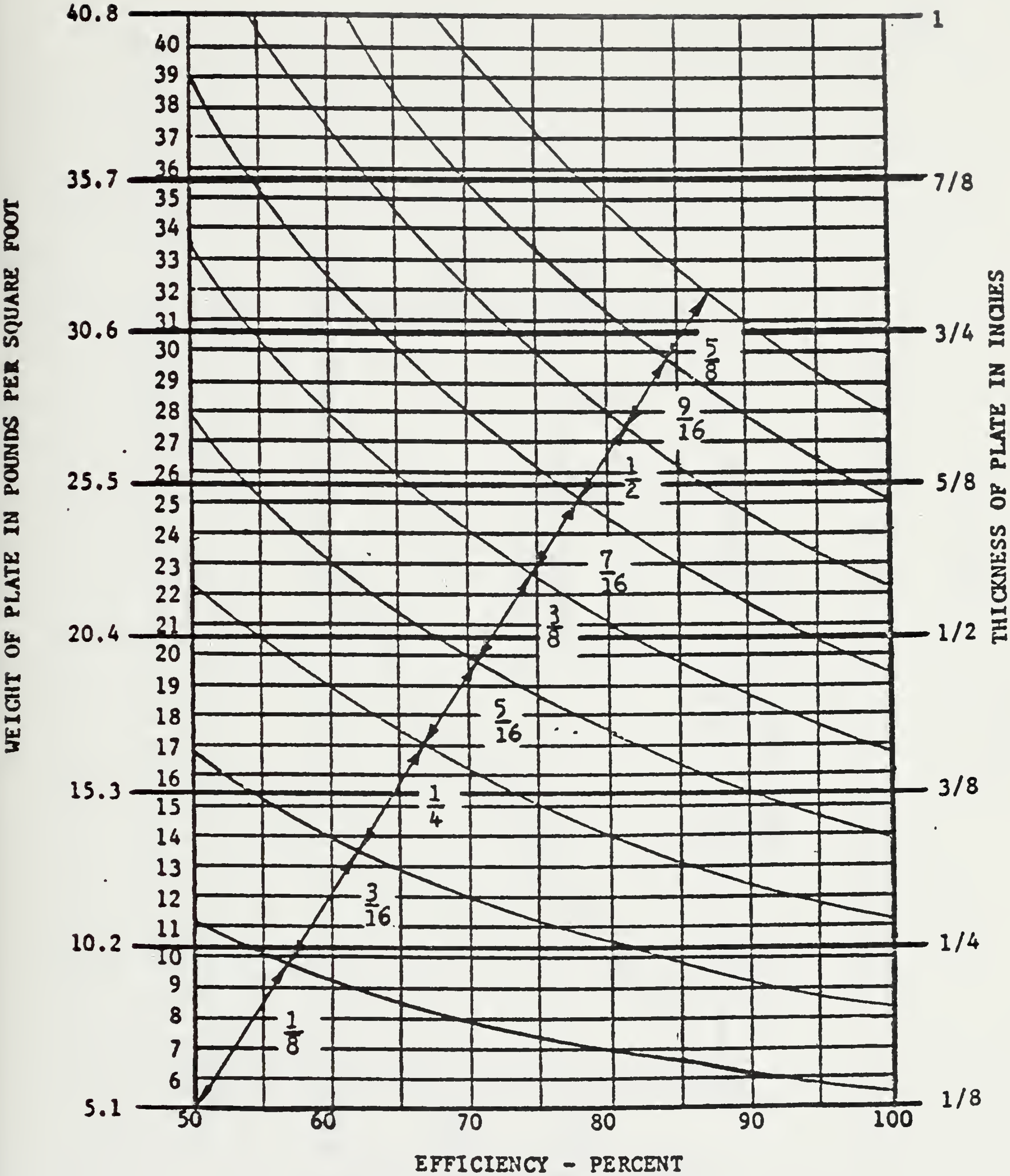
Gap. The maximum gap that is allowed without increasing the weld size is 1/16 inch. If the gap is greater than 1/16 inch, the required weld size is equal to the normal required size plus the gap. The maximum permitted gap even with increasing the weld size is 3/16 inch.

Convexity: The maximum convexity for fillet welds which varies with weld size is as shown in Figure 5.7. The weld edge shall not form a re-entrant angle less than 90 degrees with the base plate.

Size Tolerance: "Fillet welds shall not vary below the specified size." Fillet weld sizes in excess of those required by plan are acceptable, provided the fillet contour meets the above convexity requirements.

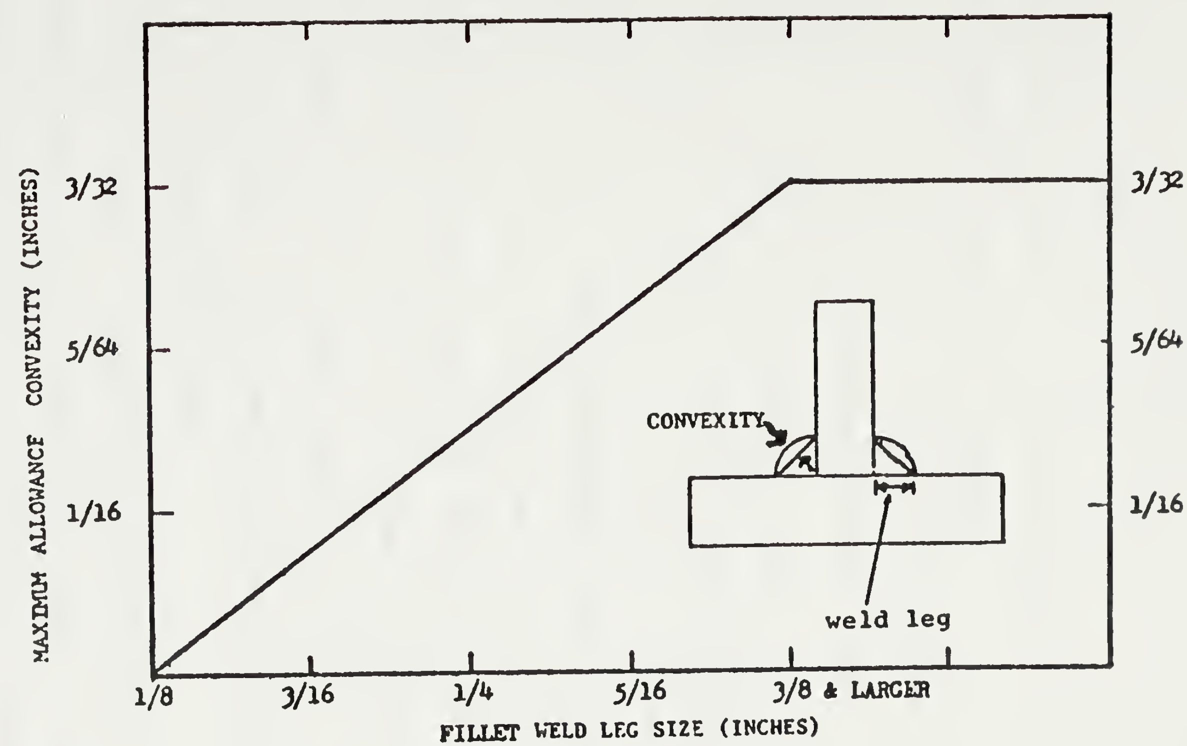
From these specifications, the importance of close fitup, regular weld bead shape and minimal undersizing is stated. These rules were born from past practice and empirical data in order to limit the probability of weld failure in service.

In the case of thin plates where welding process requirements determine the value of k, and span and thickness are selected such that Qb/t^3 or kl^2b/t^3 approach the buckling value, a small increase in fillet weld leg can easily precipitate buckling. This situation presents



Efficiency Chart for Continuous Double-Fillet Welded Tee Joints Made Between Medium Steel with MIL-601 Electrodes Based on the Thinnest of the Two Plates Joined.

FIGURE 5.6 [40]



Maximum Allowable Convexity for Fillet Weld Sizes

FIGURE 5.7 [40]

a problem to human welders who normally try to slightly oversize fillet welds to minimize the probability of undersizing.

As an example, consider the case of a stiffened mild steel panel:

Dimensions: t = 178 in. (0.452 cm)

b = 14 in. (35.6 cm)

Required Joint Efficiency: 75%

Required Fillet size: 1 = .125 in (.318 cm)

Welding Process: GMA (spray transfer)

From a survey of recommended GMA welding parameters for fillet weld application [24], the process constant for this case, k, is approximately 1.3×10^4 cal/cm^3. Hence the expected heat input for an exact 1/8 inch weld leg is 655 cal/cm. Terai's buckling limit requires that the heat input, Q, be limited to 1040 cal/cm. Therefore, the maximum allowable fillet size is .157 inch. Thus, the maximum oversize allowed to the welder is 1/32 inch. Since no undersizing is allowed by the Navy, the entire tolerance range within which the welder must work is 1/32 inch.

It is practically impossible for a human to perform this accurately at normal, economically acceptable production rates. If attempted, the welder should anticipate either reweld work due to undersizing, or buckling due to excessive heat input.

The American Bureau of Shipping [41] prescibes that under no conditions shall the fillet leg size be less than 3/16 inch, based on quality control considerations for existing welding technology. ABS has established the policy of allowing weld leg reductions up to 1/16 inch only if automatic double continuous fillet welding is used and

quality control of fitup and welding is proven.

It should be noted that rewelding undersized fillets will substantially increase the accumulated heat input and residual stresses, thus increasing the likelihood of buckling. If buckling occurs, difficult and time consuming flame straightening methods can be employed. Potential methods for reducing buckling distortion include:

a. Clamping

b. Stretching

c. Differential heating

d. Use of intermittent fillet welds

e. Use of anti-tripping brackets

f. Use of low heat input processes including laser welding.

However, each of these presently available alternatives significantly increases fabrication costs due to increased labor and/or material costs.

A second-generation seam-tracking robot with real-time feedback would offer the potential to use simple, conventional welding and fabrication processes for thin stiffened panel assembly. Its advantage would stem from its ability to control fillet dimension and heat input, within narrow tolerances, and its overall lower rework rate. Such a robotic welding system is currently being designed for this application in one American shipyard.

CHAPTER 6

METHODOLOGY OF TECHNOLOGICAL AND ECONOMIC IMPACT ASSESSMENT

Based on the discussions of preceding chapters, the application area of structural assembly appeared to be fertile territory for exploration. While qualitative and some quantitative estimates of the technical feasibility of these conceptual systems appeared promising, there appeared to be virtually no available information on their economic viability. Therefore it was decided to investigate the potential economic impact of robot arc welding on the flat panel assembly process, since this application appears to have good technical promise.

To estimate the economic potential it was necessary to study an existing panel assembly line system, develop a baseline model of this process, and determine how alternative robotic welding systems would alter the costs involved.

6.1. Baseline Panel Assembly Process

The assembly method chosen for analysis was the line method, described in Chapter 3, because it is the system used by most technically-proficient shipyards in the United States. A leading manufacturer of these systems was consulted and process estimates were derived based on supplied data. The following process description of a twenty meter wide steel panel assembly line does not present a precise accounting of any known, real assembly line. It is, however, based on actual manufacturer's data, and should be considered to be generally representative of modern line assembly systems.

The generic line assembly system is a sequential, modular system consisting of six or seven stations:

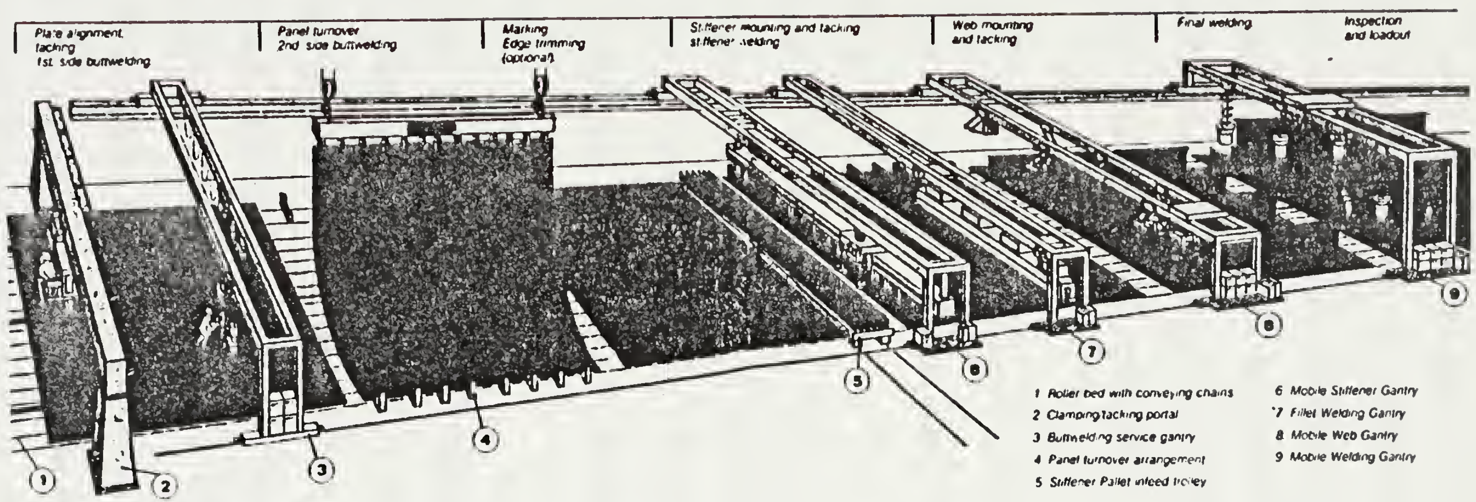
1. Plate alignment and tacking
2. Panel butt welding and turnover
3. Marking and edge trimming (optional)
4. Stiffener mounting and tacking
5. Stiffener welding
6. Web mounting and tacking
7. Final welding.

Stations, up to 20 meters wide, are spanned by overhead gantries to facilitate handling and welding, and are serviced by a continuous roller-bed conveyor system to facilitate inter-station transfer. An artist's rendering of the overall system is presented in Figure 6.1.

6.1.1. Plate Alignment and Tacking

Plates are placed at the head of the panel line in approximate position by an overhead crane in the provided landing area. The plate conveyor is used to advance the first plate through the tack welding station to a position where the trailing edge of the butt is on the centerline of the station. Similarly, the second plate is moved forward so that the leading edge is placed adjacent to the trailing edge of the first plate. Magnet manipulators are used for fine alignment of the plates. Swivel rollers allow movement of plates in any direction with minimal effort during the alignment process.

When the adjacent plate edges are properly aligned, the butt will be centered over an elevating beam that will serve as a foundation for



Example of Flat Panel Assembly Line

FIGURE 6.1

plate fairing. The beam is elevated from just below to just above the roller plane level. A powered plate fairing carriage is then moved into position for the first tack weld, and hydraulically-operated clamping cylinders are extended to fair the plate edges against the elevating beam. The operator then makes the first tack weld using welding equipment mounted on the carriage. The elevating beam, magnet manipulators, and plate conveyor are operated from a floor-mounted control panel.

After tacking, run-off tabs are attached at the butt ends by manual or semi-automatic welding to control distortion during subsequent production butt welding.

After the first butt has been tacked, the first two plates are moved downstream by the plate conveyor and the third plate is aligned in the tack welding station. After alignment, the butt is tacked as described above. The process is repeated as necessary until the plate blanket is completed.

6.1.2. Production Butt Welding and Plate Blanket Turnover

Production butt welding is accomplished by a butt welding gantry supporting one or two SAW tractors. The gantry is positioned over the first butt to be welded, and one or both motorized trolleys are driven to the transverse position over the butt where welding is to begin. The SAW tractor(s) is lowered to the plate by an electric hoist mounted on the trolley and the mechanical butt tracking device engaged, prior to commencement of production welding.

After the butt weld is completed, the SAW tractor(s) is raised by hoist and the gantry and carriage(s) are repositioned over the next butt(s) to be welded. The process is repeated until all butts have been welded.

After welding, the plate blanket is turned over with the assistance of a turnover beam and shop crane. The beam attaches to the plate blanket by a series of plate grips that are designed to evenly distribute the load. Hydraulically-activated turnover stops, arranged on either side of the panel line provide the fulcrum to effect turnover. After turnover, the second side butt welding process proceeds in the same manner described for first side welding.

It should be noted that many panel assembly lines use single-sided welding processes for plate butting. These lines, however, have their utility reduced by the limited plate thickness permitted by the single-sided process. This presents no problem when the line is not used for panels with large scantlings. However for this study, it has been assumed that American shipyards value the benefit of improved flexibility that the two-sided method gives.

6.1.3. Marking and Trimming of Plate Blanket

When required, the plate blanket is then moved by the panel conveyor to the marking and trimming station, where stiffener locations are marked and excess plate material is trimmed to final size using a portable burning tractor.

For this study, it is assumed that all plates are cut "neat" and require no trimming, a common practice that improves productivity. Panels are assumed to be either pre-marked or marked during the stiffener tacking process. Therefore, this station is assumed to be unnecessary and is eliminated from this baseline model.

6.1.4. Stiffener Fitting and Tacking

The mobile stiffener gantry regulates, fits, and tacks panel stiffeners at the next station. The previously-racked (palletized) stiffeners are brought by shop crane or rail and placed on or adjacent to the plate blanket. The mobile stiffener gantry is moved over the stiffener rack, the mounting beam is lowered, and the stiffener straightening and lifting magnets are attached to the first stiffener to be mounted. The gantry transports the stiffener to its approximate position on the plate blanket, where sensitive hydraulic controls are used to make adjustments to transverse position, longitudinal position, skew, and cant until the stiffener is aligned within ± 1/32 inches of the desired position.

The clamping trolley is then brought into position over the area of the first tack welds. The plate magnets and hydraulic ram are engaged, pulling the plate up to close the gap between plate and stiffener. Two operators, one on each side of the stiffener, tack weld both sides of the stiffener using welding equipment mounted on the clamping trolley.

The clamping trolley is moved along the stiffener and the process repeated until the stiffener is completely fitted and tacked. The

lifting magnets are then released, the mounting beam raised, and the mobile gantry moved to fetch the next stiffener. The procedure is repeated until all stiffeners have been fitted and tacked.

6.1.5. Stiffener Production Welding

The plate blanket with tacked stiffeners is moved under the fillet welding gantry, which operates over a large portion of the panel line. (This buffer capability helps reduce production flow imbalances.)

As the production welding gantry is brought into position over the first stiffener to be welded, fillet welding trolleys, with suspended welding tractors, are positioned over the stiffener as determined by the welding sequence. Lowered by electric hoist, the motorized fillet welding tractor straddles the stiffener and executes continuous or intermittent double fillet welds by means of two GMAW (or FCAW) weld heads, descending from the tractor, one on each side of the stiffener. Each motorized trolley carries the tractor cables and hoses along a cable suspension system mounted from the gantry.

Upon completion of welding, the equipment is raised by hoist and the gantry and trolley are repositioned over the next stiffener to be welded. The procedure is repeated until all stiffeners have been fillet welded.

6.1.6. Second Direction Stiffener Fitting and Tacking

The stiffened panel is moved under the mobile web gantry. The first web, girder, or similar second direction stiffener is placed into approximate position on the panel by shop crane. The mobile web gantry is brought into position and its auxiliary hoist attached to the web to assist in maintaining position.

The web fitting trolley, suspended from the gantry, is moved over the location of the first tack weld. Stiffener clamps are attached to the previously welded stiffeners, and the hydraulic system actuated, pulling the panel upward, which closed of the gap between the web and panel. The first tack welds, on either side of the web, are made using welding equipment mounted on the gantry FCAW service stations.

The mobile web gantry, fitting trolley, and FCAW service stations are moved along the web and the process repeated until the web is completely fitted and tacked. When the web is self-supporting, the auxiliary hoist and shop crane may be released.

6.1.7. Second Direction Stiffener Production Welding

After tacking, the mobile web welding gantry is used to service production welding of webs.

Using the mobile web welding gantry and its installed FCAW stations, up to six production welders may be working at one time on second direction stiffeners and hull outfitting items such as foundations, brackets, collar plates, and gussets. The service stations keep welding guns and wire feeders in proximity to the work, eliminating the need to reposition any welding equipment or to drag hoses and cables over the panel. As a result, welding operator factors are higher than average.

The capabilities of this station can be enhanced by a supplemental off-line station where unfinished hull outfitting work, including vertical fillets of stiffener intersections, can be performed along with inspection and rework activities. This arrangement helps to improve the work buffer capability of the web welding station and reduce production flow imbalance.

6.2. Alternative Robotic Arc Welding Systems

The final web welding station of the baseline assembly line was chosen as the primary location for robotic arc welding application, since the existing stiffener welding station appeared to be relatively productive and well suited for mechanized welding. Three concepts were considered for application:

1. Overhead gantry robots with x-y (horizontal) position welding capability.
2. Overhead gantry robots with x-y-z (horizontal and vertical) position welding capability.
3. Lattice welding robots with x-y (horizontal) position capability.

It was assumed that the gantry robot concepts would be matched in production capability to the needs perceived for smooth operation with the rest of the production line stations. The lattice welding concept was considered to assess the desirability of modifying the line method by combining all stiffener and web welding at the last station and eliminating the baseline stiffener welding station. By these modific-ations, it was hoped that insight might be gained to the potential of the individual skeleton and eggbox assembly methods to incorporate robotic welding systems.

The gantry robot concepts were considered to be off-line programmed from a CAD/CAM data base, requiring a single supervisor/operator for installation monitoring. It was assumed that the lattice welding robots, as described in Chapter 4 would be technologically simpler, but less capable, requiring machinery-assisted human intervention for transport

between lattices, initial positioning, and possibly simplified on-site, off-line programming.

The flat panel assembly, modified for lattice welding robots, might operate as follows. After fitting and tacking of both longitudinal and transverse members to the plate blanket, production horizontal fillet welding is accomplished at the multiple-robot welding station. Self-crawling, closed loop control robots are moved into position by electric hoist from the supporting overhead structure to commence horizontal fillet welding of the lattice. The operator moves the robot and welding head to the programmed initial position and then initializes the CAD/CAM-generated welding sequence. (Alternatively, the operator could program the approximate weld sequence using pre-set parameters and fast, high-level manual programming techniques.) Upon completion of the rectangular sequence in the lattice, the robot signals the operator by light and/or sound beacon, that it is ready to be raised by hoist, and transferred by the overhead structure to the next lattice cell. The described sequence of events continues until all horizontal fillet welding is completed. Welding should commence near the center of the panel assembly and generally progress away from its center toward its edges, so that residual stresses and distortion may be minimized. Vertical fillet welding of stiffener intersections and other hull outfitting is assumed to be accomplished by semi-automatic methods off-line.

6.3. Process Modelling

A number of methods for modelling the work flow on the panel assembly line were considered to assess the first criterion of investment decision, technical feasibility.

Use of classical single-channel queuing theory was not thought to be practical for a number of reasons. This method assumes a large or infinite source of "customers" to be served by the queuing system. The "customers" are assumed to have inter-arrival times specified by a statistical (often Poisson) distribution and the queue is assumed to have determined service rates and distributions. The process, as a whole is also assumed to be steady state, ignoring start up and phase down conditions. It is believed that a real shipyard panel line would not be operated on a continuous basis due to demand and scheduling fluctuations. Significant slack time would most likely be scheduled between major panel production changes so that production rate variability could be accommodated. Thus, relatively frequent startup and phase down would be in order. The distribution of service and arrival times, is, to a large degree, dependent on the character of the particular workforce and its management [12]. No data was available from any specific shipyard assembly line, from which distribution functions could be derived or approximated. To simply have assumed a distribution might be difficult to justify, based on their variability among different work forces [42].

Simulation using the Monte Carlo method was not considered feasible due to the lack of probabilistic distribution data for station service times. Again, it was not justifiable, to assume a particular distribution

as representative of the process. The same fundamental lack of information precluded using procedures for analyzing stochastic and multiparameter networks such as GERT (Graphical Evaluation and Review Technique) [43, 44].

The most feasible method was to simply and heuristically model the process as a tabulated sequence based on "standard" service times. Cycle time data was available from the assembly line manufacturer, based on engineered standards, derived empirically from actual time-motion studies, under "normal" operating environments [12]. Thus these data, represent expected or "average" durations of processes utilized on the assembly line. Temporal variation in these processes was accounted for by means of a single adjustment (or inefficiency) factor also derived empirically from actual time-motion study. This empirical variation also included expected times for in-buffer waiting and plate blanket movement. The manufacturer-supplied inefficiency factor was then modified to account for assembly line availability assumptions. The effects of non-steady state line operation, when the line was available, were accounted for by the input model described in the next chapter.

Given the input data from a series of panel assemblies to be fabricated, their work progress, based on derived standard process times, was traced from station to station through the assembly line and recorded. This was done for the baseline model and all alternative robot models considered. The stream of direct labor savings in man-hours was calculated for each alternative robotic model as a function of overall robot subsystem production capability. By matching the robot subsystem to the processing capacity for the rest of the production line, an

optimum level of capability could be estimated for each alternative.

To help quantify a parameter for robot subsystem production capability, some simplying assumptions had to be made. It was deemed necessary to segregate the issues of welding technology from robot technology to assess this parameter.

The first important assumption was to postulate that future robot welder travel (arc) speeds could be independent of workpiece scantlings, but still dependent on weld position. This was based on the argument that welding technology could advance to the degree that maximum arc speed would be limited by the robot and specifically its tracking and guidance processing capability. The high-deposition welding ability, required for this assumption to be valid, could be attained by developing a multi-electrode, large wire GMAW system as discussed in Chapter 4, or some other advanced multi-position robotic welding system.

Another simplifying assumption of this study was to estimate the vertical fillet welding arc speed of a candidate welding system as a fixed fraction of its horizontal fillet welding arc speed. This estimate was based on comparing recommended GMA welding parameters for comparable horizontal and vertical welds over an expected range of fillet sizes, since this type of process appears well suited to robotics. The spray transfer mode was assumed to be used for horizontal welds and dip transfer mode in vertical positions.

The use of pulse GMAW power sources for pulse spray transfer or pulse dip modes was not considered in this study. It is believed that using these methods may significantly increase the ratio of vertical arc speed to horizontal arc speed for comparable welds and equipment [45].

Their potential for robotic control and guidance should be a topic for future study.

The derived optimum production capability parameter for each alternative was assumed to be total effective arc speed (TEAS) where

$$TEAS = N_w V_w F_o \tag{6}$$

where

N_w = number of welders (human or robotic)

V_w = rated arc speed of one welder

F_o = average operating factor of welder.

Thus by assuming an operating factor and maximum rated arc speed, the number of welders, required to attain the optimum production capability of each alternative, could be determined. Alternatively, required rated arc speeds could be determined by assuming the other variables fixed, thus providing a rough gauge of required future technological improvement to production welding systems.

6.4. Cost Modelling

The second criterion of investment decision, economic practicality, is the basis for the present discussion. Of particular interest is the total cost comparison of the alternative robotic system models with the baseline system model.

Gross savings in any time period, are actually revenue for the company. This additional income is reduced by equipment depreciation before income taxes are assessed. The net income derived for each period is part of a savings stream. For a projected savings and a prescribed initial investment, the pro-forma cash flow can be determined. This commonly used method was not used in this study because the required

initial investment for the robotic systems in question cannot be prescribed.

Instead a present worth analysis, (or net present value analysis), was conducted by projecting primary and secondary costs and cost savings over a prescribed time horizon in order to determine the level of investment required to purchase and install, a proposed robotic subsystem, including changeover and startup costs. In such a manner, a qualitative assessment of the future affordability of such concepts can be made.

To calculate the value of the entire savings stream for the proposed system, the following must be factored:

- Investment horizon
- Salvage value
- Annual savings

To generate the annual savings stream for the proposed system, a number of factors should be accounted for including:

- Level of production
- Capital depreciation
- Taxes
- Investment credits
- Interest rates (cost of capital)
- Labor and maintenance costs
- Other operational costs
- Cost of quality (rework)
- Secondary, and higher order costs.

The determination of the estimated maximum allowable level of total initial investment coupled with the production capability parameter for each alternative offered a simple means of estimating cost benefit versus required technical performance. This composite indicator was chosen to be:

$$Z = \frac{\text{allowable investment cost}}{N_w V_w F_o} \tag{7}$$

CHAPTER 7

SELECTED ASSESSMENT MODELS

The models used to evaluate the various alternatives, described in the preceding chapter, are presented here.

7.1. Input Model

To evaluate and compare these alternatives, a product or series of products (panels) must be selected as input data for the assembly line process model. As such, general ship structures vary greatly with vessel type, size, route requirements, and local design customs and construction methods. To select a "typical" ship for model input data is a potentially misleading motion. It should be understood that the model results reflect the particular characteristics of a design and its construction methods. Hence, if an indepth understanding of aggregate assembly line performance for a variety of ship types is required, then data from each should be used to test process model performance. This was not done in this study because it was thought that using input data that reflected probable future design-for-production tends to be more important.

The ship structure selected for evaluation and input into the various alternative models is a Sta T32 product carrier standard tank module as built by Cammell Laird Shipbuilders Ltd., Birkenhead, England during the mid to late 1970's [46]. Its design is noted for its excellent producibility and simplicity, reflecting the direction of the current trend to more seriously value economy of construction among design goals. Basic ship and tank module characteristics are presented in Table 7.1.

Length, B.P.	163.5m
Scantling Length	162.54m
Breadth, Molded	25.91m
Depth, Molded	15.65m
Scantling Draft	11.85m
Length, LWL	167.57m
Scantling C_B=0.80 at	11.85m draft

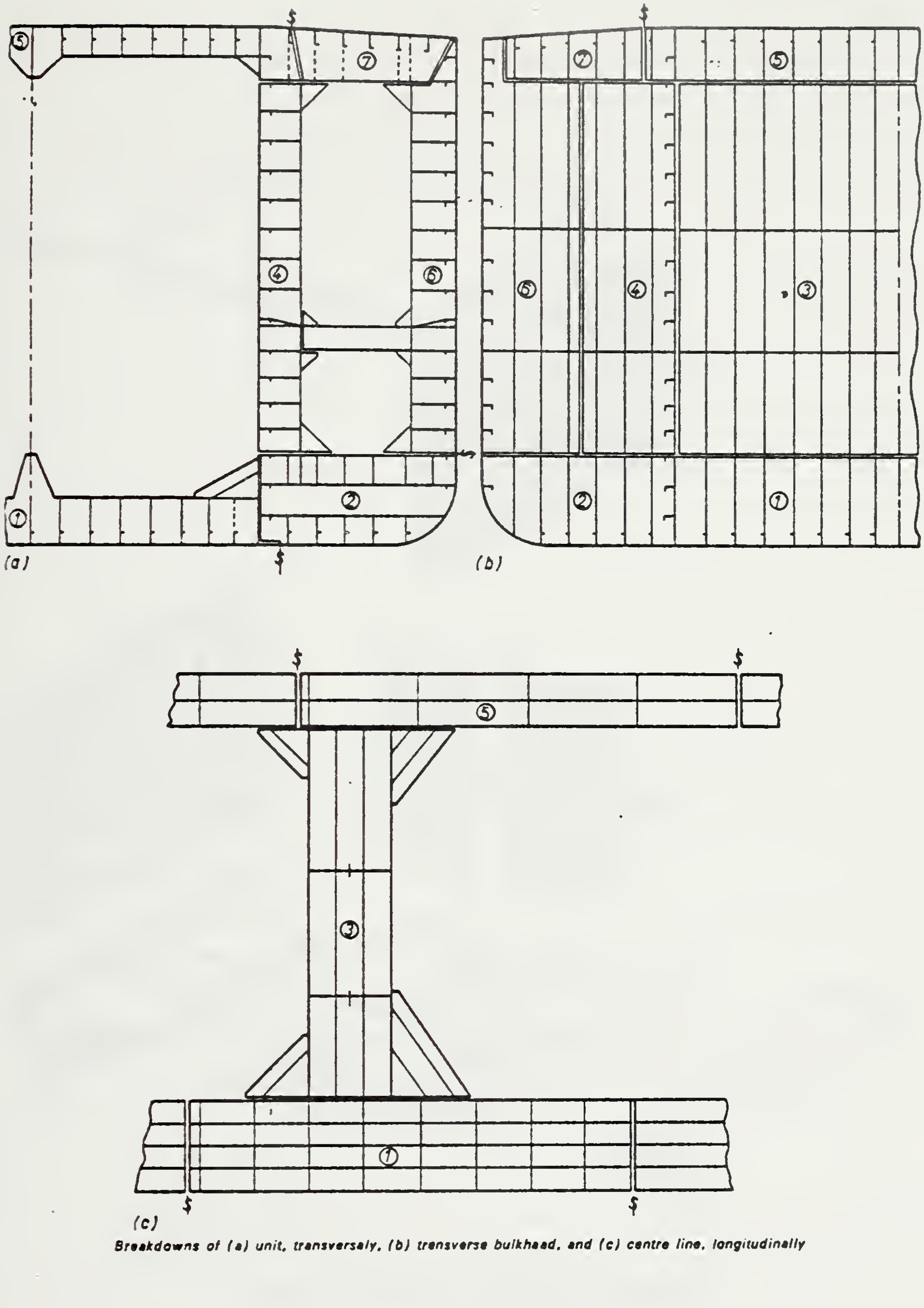
Table 7.1. Sta T 32 Product Carrier Characteristics[46]

The vessel's cargo tanks are divided into eight equal banks (modules), each subdivided into a center tank and two wing tanks. Each parallel-body module is comprised of two-dimensional panels broadly dividing the vessel into three major layers at 2.75 and 14.25 meters above baseline. See Figure 7.1. Thus the ratio of shop to ship welding is improved and the proportion of positional welds is reduced. As Figure 7.2 shows, bottom units are thus laid down as horizontal flat panels, followed by bulkheads as vertical flat panels and the cargo tanks are closed by fitting the deck's flat horizontal panels.

The major advantages of this design are:

- Component repeatability. The number of tanks economically provided in standard design, apart from operational reasons, is both a function of classification rules to protect against the effects of wave loading of slack tanks, and the shipyard production facilities, related to plate length. In the Sta T32 tanker, these considerations result in 24 tanks total. The chosen plate length is precisely equal to the tank module length, (after shrinkage allocations), facilitating either as-built or retrofit stretching of the design by one tank length. A key advantage is that shipyard scheduling problems of cargo tank steelwork, with respect to ordering, identification of part-listings and NC tapes, and routing and sequencing of material, can be significantly lessened.

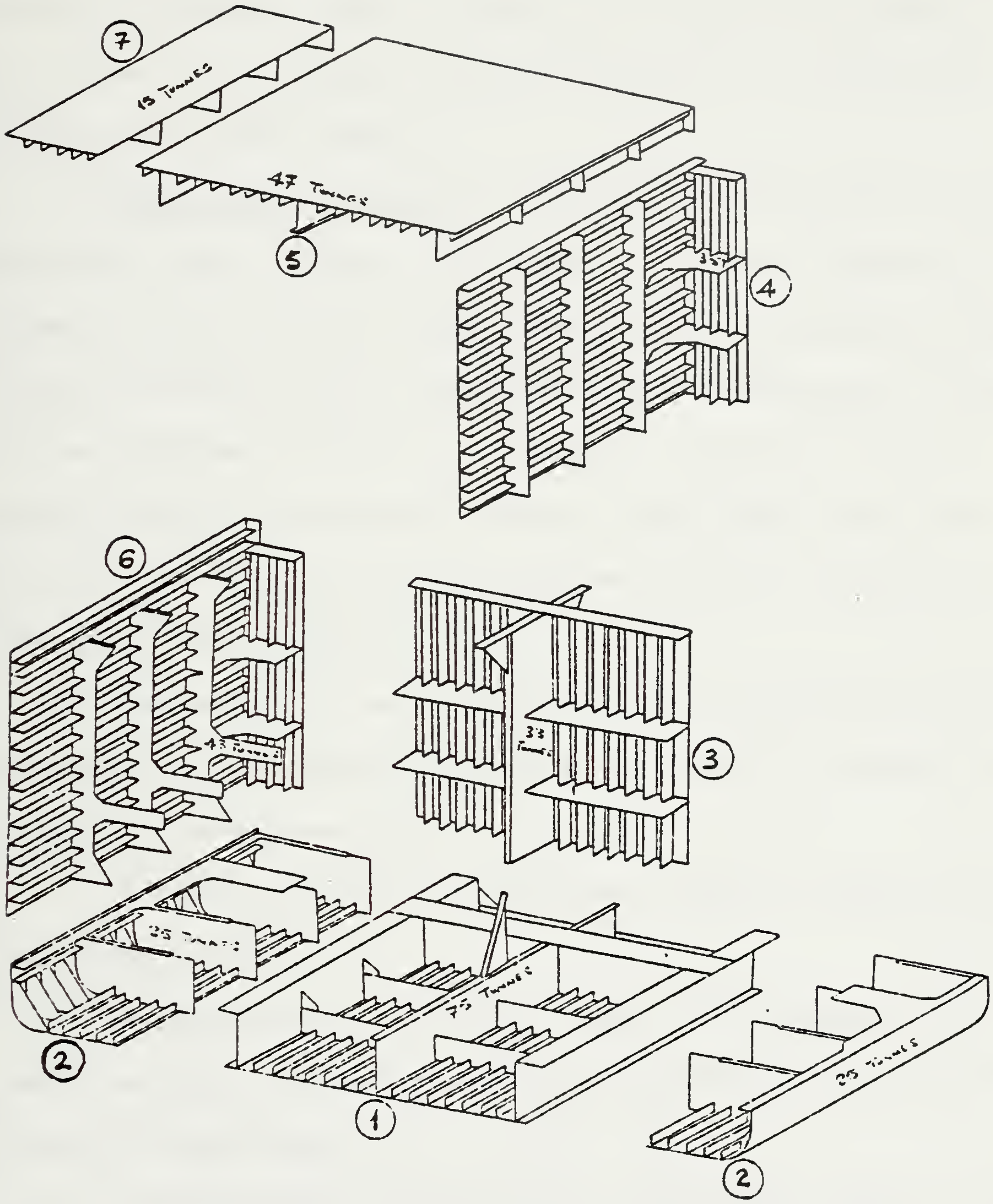
- Dimensional Control. Three-dimensional units are avoided in the cargo length because of their increased demands on dimensional control. Two-dimensional panels are used to the maximum extent and erection is planned to allow at least one direction of fitup freedom. Where necessary, fitup is augmented by use of lap joints.



Breakdowns of (a) unit, transversely, (b) transverse bulkhead, and (c) centre line, longitudinally

Sta T 32 Tank Module Panels

FIGURE 7.1 [46]



Sta T 32 Module Erection Sequence

FIGURE 7.2 [46]

- Erection Sequence. The ship is designed for pre-erected tank modules in transverse rings that are then block-erected in-berth, rather than erected in longitudinal layers in successively higher levels throughout the ship's length.

- Material/Labor Tradeoff. The extent to which extra material can be built into a design to save labor is limited. However, the judgments in selecting structural alternatives for a long-term series of ships is made difficult by uncertainties in predictions of series cost and performance indices. Fortunately, historical trends of marginal analysis tend toward increasing steel weight since steel costs are more reliably forecasted and anticipated to escalate at a slower rate than labor [46].

The information for each block panel that is pertinent as input to the assembly system models is presented in Table 7.2. The data there are based on these assumptions:

1. All panel plates are of sufficient length to require no welding of transverse butts.

2. Plating width is nominally 10 feet. (This assumption is somewhat arbitrary but reflects the actual dimension commonly available in the U.S. and Europe.)

3. All longitudinal stiffeners are continuously welded to plating on all panels, except inboard longitudinal bulk heads (panels 4-P and 4-S).

4. Longitudinal bulkhead stiffeners are intermittently fillet welded to panel plating with a weld to spacing ratio (fillet ratio) of 1:3.

Panel Number	1	2-P/S	3	4-P/S	5	6-P/S	7-P/S
Number of Plates: N_p	5	2	4	4	5	4	2
Panel Length (ft):L	32.8	32.8	37.7	32.8	32.8	32.8	32.8
# of Long. Stiffeners: N_L	14	5	14	13	14	14	5
Stiffener Fillet Ratio: FR_L	1	1	.25	.25	1	1	1
# of Xverse. Girders: N_{xG}	4	4	2.5	4	4	4	4
Panel Width (ft.):W	49.6	22.0	45.3	36.8	51	40.4	17
# of Long. Girders: N_{LG}	3	0	1	0	3	0	0
Stiffener Web Height (ft): h_L	1.5	1.5	1.6	1.0	0.7	1.0	0.7
Girder Web Height (ft): h_G	9.0	9.0	4.3	4.3	5.7	4.3	5.5
Number of Lattice Cells: N_c	66	20	48	52	64	54	24

Table 7.2. Panel Input Data

5. All transverse and longitudinal girders are continuously fillet welded to plating.

6. All girders are slotted so that only one collar plate is required to be manually welded to secure the members' intersection. This welding is accomplished at the supplementary welding/inspection station off-line.

7. Each intersection of stiffeners and girders requires two continuous vertical fillet welds, each of a length approximately equal to the lesser web height of the two members.

8. The curved bilge plating, transverse bilge stiffeners and two longitudinal side shell stiffeners of panels 2-P and 2-S are manufactured and assembled on a separate curved panel line or in a subassembly shop. The curved bilge subassembly is seam welded to a single flat plate prior to positioning and tacking of bottom stiffeners.

9. All plating is cut neat, allowing for calculated welding shrinkage, so that plate trimming may be eliminated.

7.2. Alternative Process Models

Models for five specific cases are presented:

Case B: Human semi-automatic welding of all horizontal girder fillets (Baseline case).

Case H: Gantry robot welding of all horizontal girder fillets.

Case HV: Gantry robot welding of all horizontal girder fillets and all vertical stiffener-girder intersection fillets.

Case HV*: Gantry robot welding of all horizontal girder fillets and as many vertical stiffener-girder intersection fillets as station cycle times permit. Vertical fillets are welded on an available basis, so as not to interfere with the overall production flow of the panel line.

Case E: Lattice robot welding of horizontal stiffener and girder (eggbox) fillets. Panel line modifications are as presented in Section 6.2.

Assumptions for assembly line models are:

- All assembly line stations have a single-position buffer spaced between them to allow more flexible production flow.

- Limited pre-erection facilities and manpower preclude simultaneous module erection. Modules are, instead, erected in series, the usual procedure for such tankers. Thus instead of scheduling production runs of identical panels for all ship tank modules (e.g., eight panels of design 2-P), all eleven panels of a single module are scheduled as a production run.

- Panels are scheduled to optimize panel line operations, instead of module pre-erection sequence. Thus they are ordered and arranged to minimize interstation slack (buffer) periods among the eleven panels to be assembled for each tank module.

- Production flow is discontinuous. The duration between module schedules is such that a significant slack period exists between the last panel produced in one module run and the first panel of the next module. In other words, each panel production run for a single module has start up and shut down phases.

7.2.1. Gantry Welding Robot Assembly Line Model

The model for cases H, HV, and HV^* is derived from data supplied by the panel assembly line manufacturer. The following standard activity descriptions are assumed to be generally representative of a generic assembly line system, and should not be interpreted to describe an actual assembly line of any particular manufacturer.

They are:

1. Station 1 (Plate Alignment and Tacking)

Activity	Duration (minutes)
- Land Plate	5
- Move plates into station, align butts	5
- Tack butt - one tack every 18 inches, at 1 minute per tack	2L/3
- Weld run-off tabs - at 5 minutes per tab or 10 minutes per butt	10

2. Station 2 (Panel Turnover and Butt Welding)

Activity	Duration (minutes)
- Position tractor to butt weld	3
- Set up tractor for butt weld	5
- Weld SAW, at single-pass travel speed of 30 inches per minute (2.5 fpm)	L/2.5
- Plate Turnover	15

(Number of station operators and tractors: 1 or 2)

3. Station 3 (Stiffener Fitting and Tacking)

Activity	Duration (minutes)
- Fetch and position stiffener	3
- Tack weld - two tacks (one each side of stiffener) every 30 inches/pair for rate of 5 fpm.	0.2L

(Number of station operators: 2)

4. Station 4 (Stiffener Production Welding)

Activity	Duration (minutes)
- move tractor in position for double fillet weld	2
- Set up tractor for double fillet weld	5
- Weld, FCAW using up to 1/8 inch diameter wire, at rated arc speed of 20 ipm; rapid transfer speed of 50 ipm	$[0.6FR_L + 0.2(1-FR_L)]$

(Number of station operators: 2)

(Number of tractors: 1 or 2)

5. Station 5 (Girder Fitting and Tacking)

Activity	Duration (minutes)
- Position Girder, attach fitting tool	10
- Tack weld two tacks (one each side of web) every 30 inches at 1.5 minutes per pair, one welder each side of web, for rate of 20 ipm.	0.6L (Long. girder) 0.6W (Xverse. girder)

(Number of station operators: 2)

6. Station 6 (Girder Production Welding)

Activity	Duration (minutes)
- Weld girder to plate depositing continuous fillet at horizontal arc speed of V_w and operator factor F_o, using N_w welders.	$2L/N_wV_wF_o$ (long. girder) $2W/N_wV_wF_o$ (Xverse. girder)

For the manual baseline case:

V_w = 20 ipm, using semi-automatic FCAW, based on rated arc speeds for average panel scantlings and multi-diameter, single wire capability

F_o = 50 percent (manufacturer's data).

- Weld girder web to stiffener web, depositing two continuous vertical fillet welds per intersection. Vertical arc speed is determined to be approximately 40 percent of horizontal arc speed based on survey of vertical dip transfer and horizontal spray transfer GMA processes [18]. Operator factor, F_o is assumed to be unchanged.

  $5h_L/N_w V_w F_o$ (stiffener-girder intersection)

  $5h_G/N_w V_w F_o$ (girder-girder intersection)

7. Off-line Welding and Inspection Station

Manual off-line welding of hull outfit items and vertical fillets assumes the use of the same type of welding equipment and performance parameters cited for Station 6.

7.2.2. Lattice Welding Robot Assembly Line Model

The production model for Case E is basically the same as the preceding model, with two fundamental changes: the elimination of the stiffener welding station, in conjunction with the incorporation of stiffener welding at the lattice welding station (Station 6E).

The activity and duration information for Station 6E horizontal welding is practically the same as that for Station 6 in the preceding model. However it is different, due to the requirement to model human operator interaction with the crawling lattice welding robots.

Human intervention requires the determination of the number of welding robots that can be practically supervised in a production setting by one operator. Since he is required to control inter-lattice transport, sequence initiation, and possibly fast on-site preprogramming, this is an important issue of productivity and safety.

It is easily understood that maximum handling time allowed for robot transfer and initiation is a function of the number of robots for which the operator is responsible and the time it takes the robot to weld the lattice fillet pattern. Analysis is fortunately simplified

by the regular nature of the selected input data. It is noted that all complete lattices of all panels are approximately 8.2 foot by 2.8 foot rectangles, with the exception of the transverse bulkhead, panel 3, which has 12.6 foot by 2.8 foot lattices. Thus the standard lattice for 10 of 11 panels has a perimeter of some 22 feet. The expected time to execute the rectangular weld pattern is determined by dividing the perimeter by the arc speed, $V_w F_o$. The maximum (expected) handling time for a single interlattice transfer is approximately:

$$t_{LH} = \frac{\text{Latice Perimeter}}{V_w F_o \; (N_{wR}/N_{wo} - 1)} \tag{8}$$

where N_{wR} = Number of welding robots

N_{wo} = Number of welding robot operators.

Consequently the expected handling time for an entire panel is:

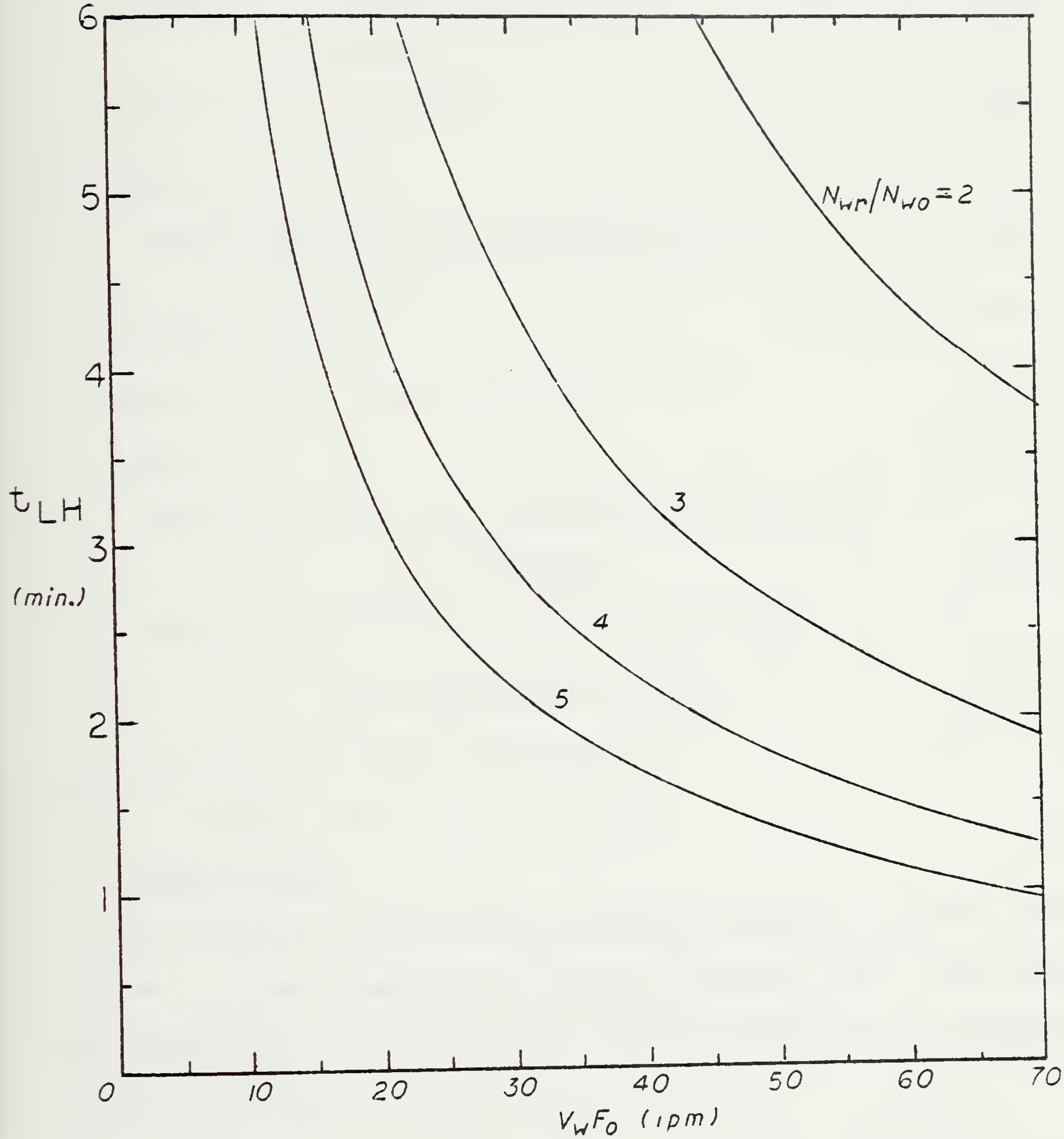
$$t_H = \frac{t_{LH} N}{N_{wR}} = \frac{(\text{Perimeter}) N_c}{V_w F_o N_{wR} (N_{wR}/N_{wo} - 1)} \tag{9}$$

where N_c = Number of panel lattice cells.

To better understand the relationship of maximum handling duration and arc speed, Equation (8) is plotted in Figure 7.3. This relationship should be checked after an optimal effective arc speed, based on a criteria of balanced production flow, is found, in order to determine if the resulting maximum allowable robot handling is reasonable.

7.2.3. Station Cycle Times

Based on the preceding modelling the following standard cycle time estimates were derived for each assembly line station in the cases considered.



Correspondence of Arc Speed and Inter-cell Handling Time

FIGURE 7.3

Station 1: $t_1 = (N_p - 1)[20 + 2L/3] + 5$ (10a)

Station 2: $t_2 = 2[8 + L/2.5](N_p - 1) + 15$ (10b)
(1 tractor)

Station 3: $t_3 = N_L(3 + 0.2L)$ (10c)

Station 4:

- Cases H, HV, HV*: $t_4 = N_L/2[L(0.4FR_L + 0.2) + 7]$ (10d)
(2 tractors)

- Case E: $t_4 = 0$ (10e)

Station 5: $t_5 = N_{xG}[10 + 0.6W] + N_{LG}[10 + 0.6L]$ (10f)

Station 6:

- Cases H, HV, HV*: $t_6 = [1/(N_w V_w F_o)][N_{xG}(2W + 5N_L h_L) + N_{LG}(2L + 5N_{xG} h_G)]$ (10g)

- Case E: $t_{6E} = [1/(N_{wR} V_w F_o)][2(L(N_L + N_{LG}) + WN_{xG} + XN_c)/((N_{wR} V_w)(N_{wR}/N_{wo} - 1))]$ (10h)

where $X = \begin{cases} 22 \text{ ft. (All panels except Panel 3)} \\ 30.8 \text{ ft. (Panel 3)} \end{cases}$

7.3. Economic Models

The alternative process models are used to generate a savings stream expressed in terms of manhours of labor per production run. This becomes input data for the cost model which, described in Chapter 6, is explained in more detail here.

7.3.1. Annual Savings Stream

The component factors for annual costs are modelled.

- Level of Production

$$L = QP/2000 \qquad (11)$$

where L = Level of production (A utilization factor based on number of shifts and production system availability) (shifts)

Q = Production period of unit system output (hours /module unit)

P = Annual production volume (module units produced/year)

2000 = Number of hours/shift-year.

Based on manufacturer's data, aggregate long term line throughput times are routinely multiplied by a factor of 1.2 to account for plate transport, inherent system inefficiencies, and panel design variations. To account for assembly line maintenance and operator personal time it is suggested that overall assembly line availability be estimated at about 85 percent. Therefore based on the way L is defined above the maximum value of L is estimated as:

$$L_{max} = 0.7s \qquad (12)$$

where s = Number of shifts of daily production operation.

- Capital Depreciation. Use of depreciation allows companies to recover their capital investment over some useful life. The effects of depreciation are to reduce the revenue subject to taxes and also to reduce the book value of an asset. The most rapid rate of return is desired, so companies in the past have most often used depreciation methods that depreciated the investment as quickly as possible. The sum-of-the-years-digit method was a favorite, returning nearly 75 percent

of the investment in half the equipment economic life.

However the Economic Recovery Act of 1981 substantially changed the laws relating to personal and corporate income taxes, including depreciation. Property placed in service after 1981 must use the accelerated cost recovery system (ACRS). Under ACRS, the cost recovery in j-th year of an asset's cost recovery period is calculated by a factor found from prescribed tables. Depreciation in year j then equals:

$$d_j = (\text{initial cost})(\text{factor})$$

The initial cost is <u>not</u> reduced by the asset's salvage value for ACRS calculations. The factor depends on the asset's cost recovery period. Selected R and D equipment and machinery can be depreciated over 3, 5, or 10 year periods, depending on their purpose and expected useful service life. Thus a 3 or 5 year depreciation period is an attractive proposition, and probably allowable, under current tax laws, for the robot systems under consideration. (The merits of 3 versus 5 years will be determined by examining investment tax credit law.) The recovery factors (x_j) for 3 and 5 year recovery periods are [47]:

	Recovery Period	
year (j)	3 years	5 years
1	.25	.15
2	.38	.22
3	.37	.21
4		.21
5		.21

- Taxes. Assuming an organization pays f percent of its profits to the federal government and s percent to state government as income taxes, and if state taxes paid are recognized by the federal government as expenses, then the composite tax rate is

$$T = s + f - sf \tag{13}$$

For this model, it is assumed that the company is incorporated in a "tax-haven" state and that T=0.48 [47].

- Investment Tax Credits. Investment tax credits for the purchase of assets are allowed in the year of purchase. They represent a direct reduction to taxes paid. These credits are a fraction of the asset's cost:

TC (tax credit) = (initial cost)(decimal amount)

where the decimal amount is taken from the following:

life (years)	decimal amount
1	.02
2	.04
3	.06
4 or more	.10

Therefore, it can be readily shown that the depreciation period providing the greatest total savings, accounting for depreciation and investment tax credits is 5 years over the range of normal interest rates [47].

- Interest Rates (Cost of Capital). The discount rate for NPV analysis is assumed to be the net rate at which the company could invest its capital in reasonably liquid securities, adjusted for inflation. This is based on the assumption that the shipbuilding firm will not borrow money for the initial costs. As an alternative this rate could

be set according to the interest rate charged by a bank for a capital acquisition loan. To assume a single rate for analysis is too presumptive and a range of rates will be examined.

In this study, inflation effects are studied in the aggregate. In other words, all component costs (e.g., maintenance, labor, insurance, etc.) are assumed to grow by equal annual rates. Therefore a simple equation for net cost of capital can be derived [12]:

$$1 + r' = (1+r)/(1+i) \tag{14}$$

where r' = net interest rate, after inflation

r = gross interest rate, before inflation

i = inflation rate.

Inflation rates used in this study are based on Congressional Budget Office projections [48] and averaged over the next five year period. The resulting assumed average rate of inflation is 6.25 percent, per annum.

- Labor and Maintenance Costs. Maintenance costs are estimated by using a simple method described by Engelberger [13], based on a percentage of initial cost. Auto industry managers commonly estimate average annual maintenance costs at 10 percent of production equipment initial cost, assuming double-shift or 4000 hour/year operation. It was assumed that current limited demand for ship production in U.S. shipyards warranted cost estimation based roughly on single-shift operation. Assuming a certain number of maintenance requirements are fixed with respect to equipment-hours, an estimate of 7 percent of initial cost was established for annual maintenance.

Labor costs are expressed in terms of annual savings streams based on differential labor costs of alternative and baseline system models.

All contributing costs and savings are physically expressed as equivalent manhours, since direct labor savings is the largest single component. This practice allows the analysis to be made without making initial assumptions on the dollar costs of labor. This was considered necessary because of significant variation in welder labor rates around the country and because of uncertainty in assumed overhead rates. It should be understood that some overhead costs, figured in direct labor overhead rates, are fixed, such as supervision, design and engineering, administration, and production services. Most of these shipyard costs remain regardless of the assembly line system considered. The correct labor rate to use is one that accounts for a welder's wages and associated variable overhead costs (e.g., health care, training, etc.) only.

- Other Operational Costs. Annual insurance costs were estimated at one percent of initial investment cost and were combined with the maintenance cost estimate to produce a combined annual rate of 8 percent.

Differences in consumable costs among the alternative systems was not considered. It was assumed that weld wire consumption is a function of joint requirements and is independent of characteristic differences among the alternative systems. Shielding gas consumption, inversely proportional to rated arc speed for given weld deposition, was also ignored. This simplifying assumption seemed acceptable since shielding gas costs associated with GMA (MAG and FCA) welding are relatively small [30].

- Cost of Quality. Rework costs were estimated by using a simple factoring method. Productivity factor, F_p, is defined as a ratio of productive time ("total time less rework time") to total time, expressed as a percentage. Here rework time is equated to repair preparation time plus actual repair time plus lost productive time.

Estimates of F_p for manual semi-automatic welding and robotic welding are 0.85 and 0.98, respectively, based on available information [7]. (The estimate for semi-automatic welding was supported by proprietary data from one shipyard using line panel assembly methods. The productivity factor for mechanized fillet welding was estimated at 0.90.)

Inspection costs were not included in this model, due to lack of good information. This oversight can be partially ameliorated by considering that initial NDT costs are dependent on written inspection requirements of agencies and not directly on the quality of work performed. However post-repair reinspection is directly dependent on detected quality.

The resulting estimate of quality related manhour cost per module unit for each of the different welding systems employed on the alternative assembly lines is

$$[(1-F_p)/F_p][\text{actual arc time/module}] \times (N_w V_w F_o)/(V_w F_o)_{mw}$$

where $(V_w F_o)_{mw}$ is the effective arc speed of manual semi-automatic welding involved in rework.

- Secondary and Other Costs. A certain amount of indirect labor cost was accounted by the process model, in as far as the various alternative robot subsystems collaterally affected the work flow and

manhour requirements at other assembly line stations.

Robot system reliability and resulting availability costs were based on the assumption that when a robot welding system was down, its capacity would be replaced by equivalent human welders. The analysis also assumed that availability costs associated with human welders, (e.g., sick days, training days, etc.), were already accounted in the variable overhead costs factored in the labor rate. The system availability of robotic welders will vary from system to system, but a target design availability of 0.98 is common in present systems [13]. This figure was therefore assumed for the analysis at hand.

Hence the unit availability cost is

$$[1 - \text{Avail}_{wR}]\ (N_{wR})[(V_w F_o)_{wR}/(V_w F_o)_{mw}]$$

where the last term is the effective arc speed ratio comparing welding robots and manual welders.

No other secondary or higher order costs were considered.

7.3.2. Lifetime Savings Stream

To utilize the described factors of the annual savings stream for calculating savings over the life of the investment, supplementary information is required.

- Investment Horizon. This evaluation must be based on projected physical lifetime of the proposed system, and its estimated useful economic life. Engelberger [13] estimates the average physical robot lifetime at 8 years. The latter factor is a function of rate of change of available technology.

In any case, the concern for short term payback of investment, among American industry, is a contractionary factor. American managers like to see one, two, or three year payback periods for investments of

their hard cash. However for this analysis, it is assumed that they are more accepting of capital risk and are willing to commit funds for a longer period, the most likely being the 5 years corresponding to the assumed depreciable lifetime. In any case the investment horizon (H) should never be greater than the physical lifespan. Thus lower and upper bounds of 3 and 5 years are tentatively set for the investment horizon, consistent with American practice.

- Salvage Value. The salvage value of a candidate system at the end of its lifetime is assumed to be zero. This assumption seems valid based on the high rate of technological change in the robotics field [49].

7.3.3. Resulting Equations

The equations synthesized from the above descriptions are presented. Because annual maintenance and insurance costs were estimated based on the initial investment, it was more convenient to aggregate these costs and factor them separately from the other annual costs.

The maximum acceptable investment cost is

$$C = \frac{(1-T)[\Delta K(P/A,\ r'\%,\ H)]}{[1/(1-TC)][1-T\sum_{j=1}^{H} X_j(P/F,\ r'\%,\ j)][1+0.8(P/A,r'\%,H)]} \tag{15}$$

where

C = Investment cost

T = Tax rate

ΔK = Annual savings stream

TC = Investment tax credit

X_j = Allowable depreciation in year j

r' = Net interest rate, after inflation

H = Investment horizon

and where

Single Payment Present Worth Factor,

$$(P/F,\ i\%,\ n) = (1+i)^n \tag{16}$$

Equal Series Present Worth Factor,

$$(P/A,\ i\%,\ n) = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{17}$$

The last term of the denominator of Equation (15) accounts for the lifetime stream of annual maintenance and insurance costs.

The annual savings stream, ΔK, is comprised as follows:

$$\Delta K = \Delta KL + \Delta KI + \Delta KA + \Delta kQ \tag{18}$$

where

ΔKL = annual direct labor cost savings

ΔKI = annual indirect labor cost savings

ΔKA = annual availability cost savings

ΔKQ = annual quality cost savings.

The component annual savings are:

$$\Delta KL = (\Delta kl)(R) \tag{19}$$

where Δkl = Per module direct labor savings (manhours),

$$\Delta KI = (\Delta ki)(P) \tag{20}$$

where Δki = Per module indirect labor savings (manhours),

$$\Delta KA = 2000L\ (1\text{-Avail.}_{wR})(N_{wR})[(V_w F_o)_{wR}/(V_w F_o)_{mw}] \tag{21a}$$

where $\text{Avail.}_{wR} = 0.98$

$(V_w F_o)_{mw} = 10$ ipm

Hence,

$$\Delta KA = 4L(N_w V_w F_o)_{wR} \tag{21b}$$

and

$$\Delta KQ = KQ - KQ_{Baseline} \qquad (22)$$

where

$$KQ = \sum_{stations} [(P(1-F_p)/F_p)[\text{actual arc time/module}] \times$$
$$(N_w V_w F_o)/(V_w F_o)_{mw}] \qquad (23)$$

CHAPTER 8

RESULTS

The baseline assembly line model was tested in different configuration variations for the 11 panel production run. Production scheduling itself was optimized for minimum slack time and maximum throughput for baseline and alternative conditions.

The scheduling sequence found to give the best results was not the erection sequence but was according to this schedule:

Panel	Order
4-P	first
4-S	↓
3	
7-P & 7-S	
2-P & 2-S	
6-P	
6-S	
1	
5	last

Because panels 7-P, 7-S, 2-P and 2-S are significantly smaller than the other panels, it proved beneficial to cycle these through the system in tandem, in order to maintain reasonable balance throughout the production run. This ordering of plates was used for the baseline and all subsequent models.

Various model runs for baseline configuration variations were performed. The welding equipment that proved to best meet the needs of the system to process the given input panels consisted of a single butt welding tractor at Station 2, two stiffener fillet welding tractors at Station 4 and three human welders operating semi-automatic FCAW systems at Station 6. (Assumed $(V_w F_o)_{mw}$ was 10 ipm.) The

criteria for welding equipment selection, relatively balanced flow with minimal overcapacity, were met.

It was discovered that the inherent bottleneck in this assembly line system design varied from plate to plate. Nevertheless panels as a whole spent significantly more time in down-line inter-station buffers than up-line, as expected. The baseline results showed good prospects existed to take advantage of the added capabilities that the alternative systems offered.

8.1. Alternative Process Model Results

The required nominal operating time to man Station 6 for a single 11 panel production run was established as a function of TEAS, total effective arc speed for each alternative case considered.

Case H was calculated based on 100 percent accomplishment of required girder horizontal fillet welds, within the contraints of balanced production line flow. An upper limit of TEAS was established based on the value for which an increase would yield no more reduction in any individual buffer duration between Station 5 and Station 6. Any capability above this level would only reduce Station 6 operating time and associated labor costs slightly. This is because at such a level, the only source for operating time reduction comes from the last panel of the production run. A theoretical lower bound for TEAS was established to meet the 100 percent accomplishment criteria, based on an inter-station buffer capacity of an infinite number of plate positions. The upper bound of TEAS was selected to represent the optimal level of production capability, because it promised 100 percent

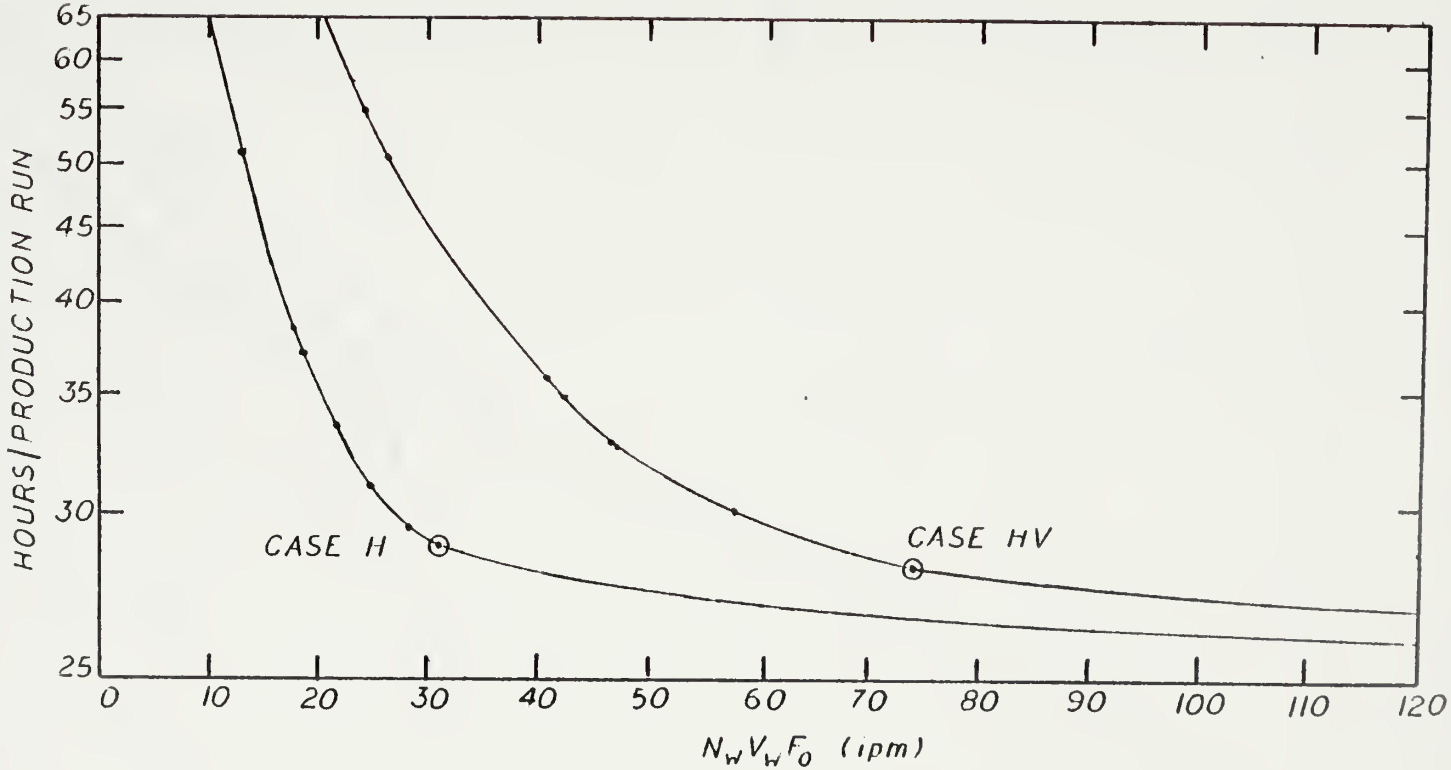
production completion with single capacity inter-station buffers.

The resulting Station 6 operating time per production run, as a function of TEAS is shown for case H in Figure 8.1. The optimal upper TEAS limit for this case was found to be 30.83 ipm. This result is consistent with the assumptions for the baseline configuration which was chosen to have a TEAS of 30 ipm, (3 welders at 10 ipm/welder). The case H lower bound was 21.65 ipm. The resulting Station 6 production run duration for optimal TEAS was 28.97 hours.

The same methodology was used for case HV, except that calculations were based on 100 percent accomplishment of required horizontal and fillet welds. The resulting optimal and lower bound TEAS were 74.15 ipm and 44.06 ipm respectively. Figure 8.1 also depicts this case, showing an optimal point duration of 28.13 hours.

To establish labor cost savings for case HV, it was necessary to determine the number of manhours of offline vertical fillet welding saved by the robot's vertical process capability. This was established by assuming $V_w F_o$ for manual offline work at 10 ipm per welder. Based on balanced flow criteria, schedule, and the vertical welding requirement for each panel, the manhours of saved manual fillet welding as a function of equivalent horizontal TEAS were established. The results for each panel are shown in Figure 8.2. These results were summed to yield Figure 8.3, saved vertical welding for the entire production run. For optimal TEAS, 67.04 manhours of manual vertical work are saved per tank module.

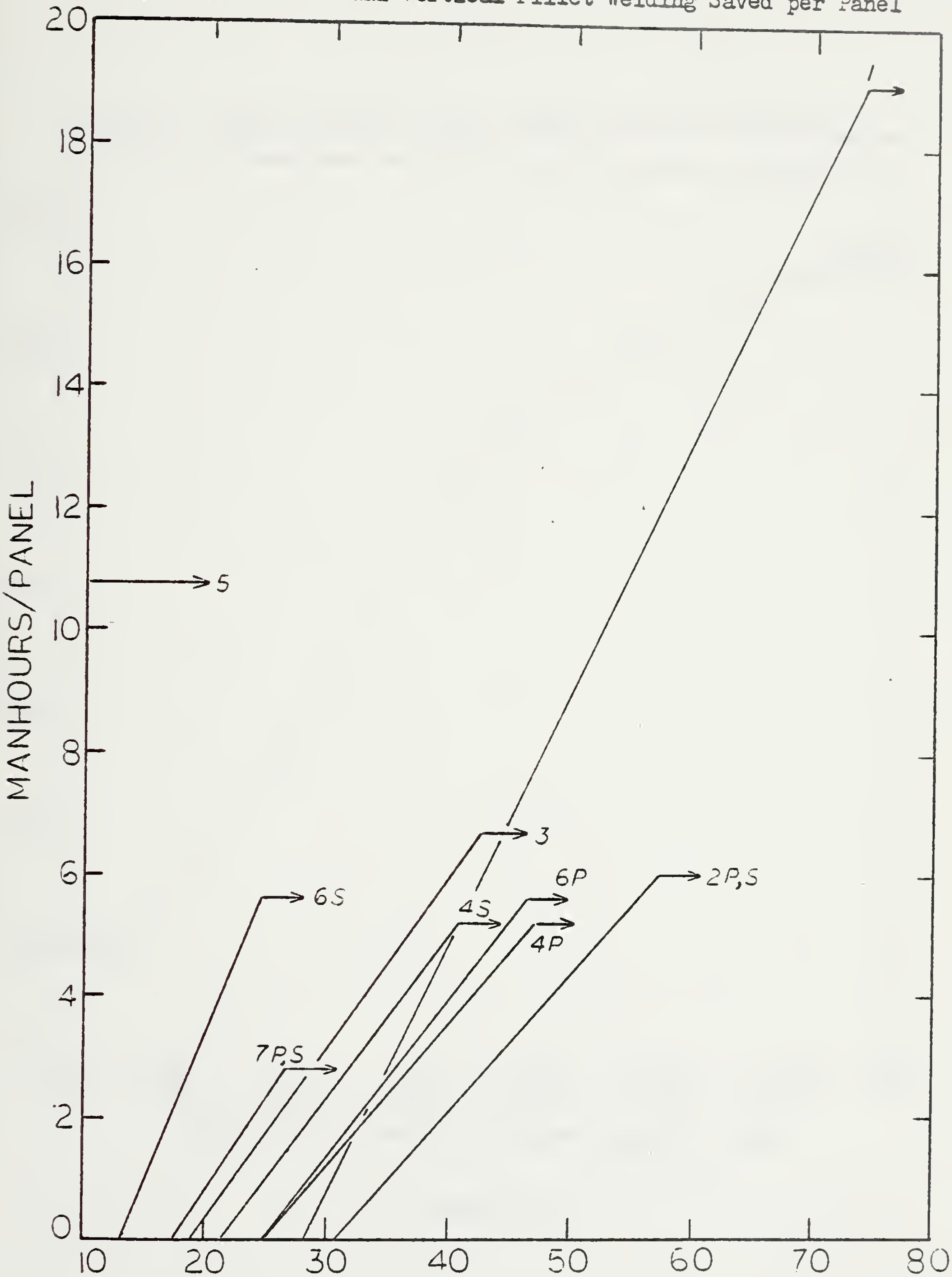
Case HV^* was included to explore the performance of a system designed to accomplish 100 percent of girder horizontal fillet require-



Station 6 Operating Times for Cases H and HV

FIGURE 8.1

Case HV: Manual Vertical Fillet Welding Saved per Panel



Effective Horizontal Arc Speed, $N_{wR}V_wF_o$ (ipm)

FIGURE 8.2

Case HV: Manual Vertical Fillet Welding Saved per Production Run

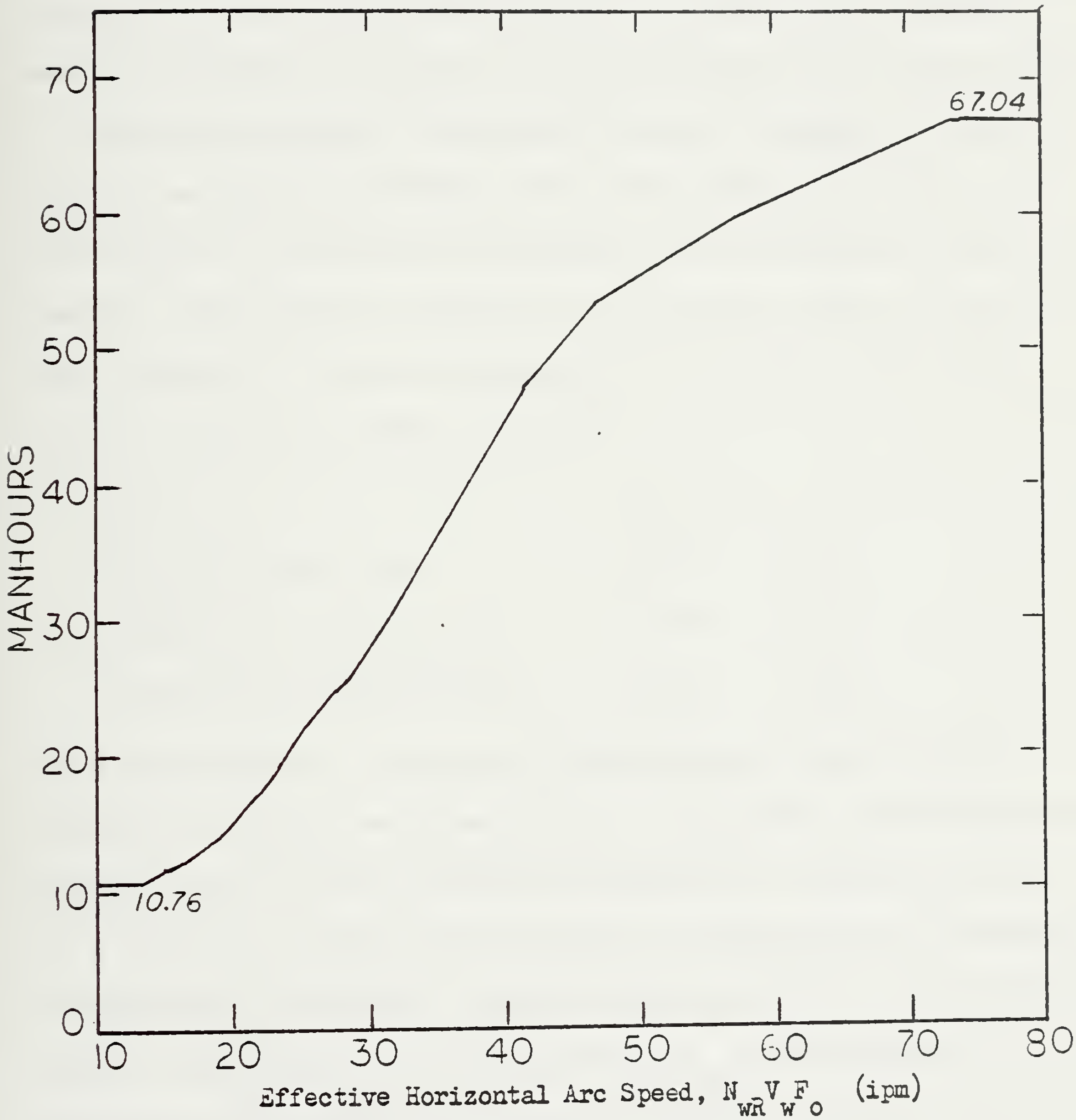


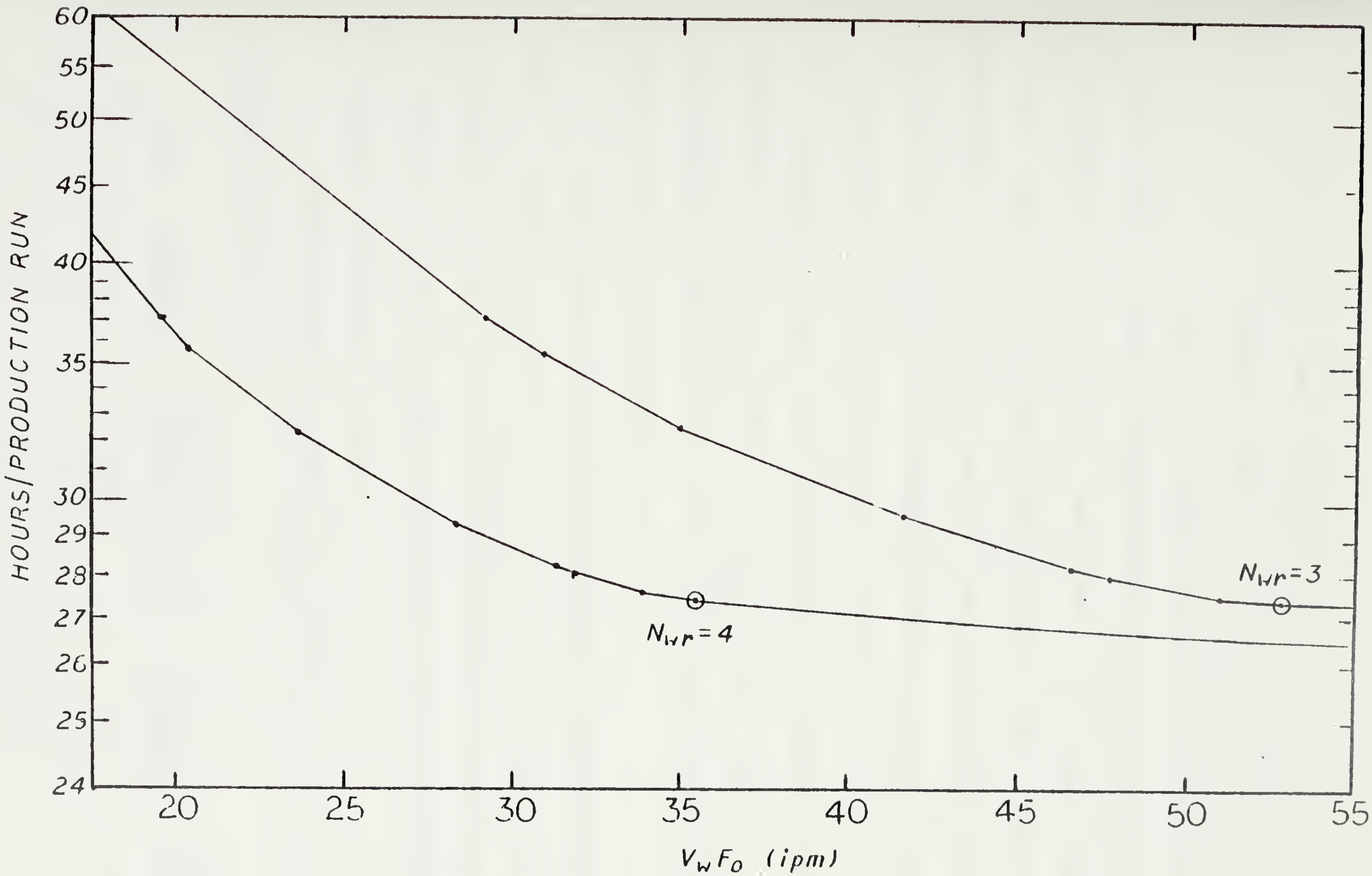
FIGURE 8.3

ments and to weld vertical fillets on an available basis whenever slack time permitted. Thus optimal TEAS is set by horizontal fillet requirements alone, at 30.83 ipm as in case H. The resulting Station 6 duration is also the same as in that case. However saved vertical welding, determined by Figure 8.3 is 17.24 manhours per production run.

Case E was modelled, eliminating Station 4 (stiffener welding) duration and using the modified cycle time, equation (10h), for Station 6E, to incorporate all horizontal fillet welding and inter-lattice handling. The model was checked for two instances, where the ratios of robot welders/robot operators, (N_{wR}/N_{wo}), were 3 and 4. The results, partially depicted in Figure 8.4, are:

N_{wR}/N_{wo}	3	4
$(N_{wo}V_wF_o)$optimal, ipm	52.76	35.47
$(N_{wo}V_wF_o)$lower bound, ipm	44.44	29.77
Station 6E Run Duration, hrs.	27.44	27.44

These were based on a 100 percent accomplishment criteria for all horizontal stiffener and girder fillets. For single operator/supervisor manning it was felt that the required effective arc speed (V_wF_o) of 52.76 ipm, was too high to be practically accomplished with foreseable future welding technology, with the possible exception of high-energy lasers. Therefore for the instance of N_{wR}/N_{wo}=3, two operator-supervisors would probably be needed to control a total of 6 robots, each operating at a rated effective arc speed of 26.38 ipm. The case for N_{wR}/N_{wo}=4 seemed more attractive in light of this, requiring one operator-supervisor for four robots, each effectively welding at 35.47 ipm.



Station 6E Operating Times for Case E

FIGURE 8.4

The question of human performance had to be checked at this point. Figure 7.3 was consulted to establish inter-lattice handling times based on values of $V_w F_o$. For single operator-supervisor manning, the N_{wR}/N_{wo} cases of 3 and 4 yielded maximum inter-cell handling times of 2.48 minutes and 2.51 minutes, respectively. The nearly identical results indicate that neither single operator system offered a distinct advantage over the other, in terms of human interaction factors. It was believed that the required handling times were probably achievable on a production basis, provided no local operator programming was required. This finding lends additional justification to the Navy's efforts to establish off-line programming of welding robots. Based on this analysis, the candidate configuration of four lattice robots and one operator was chosen as the representative for case E.

For each of the above alternative cases, it was determined that the total Station 6 (or 6E) operating time for a single production run represented the panel line's production period of unit system output, Q. This fact helped to assess the effects of level of production, L, on projected annual labor savings.

The resulting welding manhour requirements per production run are summarized for each case:

Case	Station	Operating Duration (hrs)	Manning	KL/module (manhours)
B:	4	23.86	2	47.72
	6	29.14	3	87.42
H:	4	23.86	2	47.72
	6	28.97	1	28.97

Case	Station	Operating duration (hrs)	Manning	ΔKL/module (manhours)
HV:	4	23.86	2	47.72
	6	28.13	1	28.13
	Saved Vertical Work:			-67.04
HV*:	4	28.86	2	47.72
	6	28.13	1	28.13
	Saved Vertical Work:			- 17.24
E:	4	0	0	0
	6E	27.44	1	27.44

Table 8.1

Consequently the direct labor savings per production run, ΔKL/module, were found to be:

H:	58.45	
HV:	126.33	(manhours/module)
HV*:	75.67	
E:	107.72	

As a result, the annual direct labor savings, ΔKL, were found to be

Case	Q(hrs)	ΔKL (manhours/year)
H	28.97	58.45P or 4035.2L
HV	28.13	126.33P or 8981.9L
HV*	28.97	75.67P or 5224.0L
E	27.42	107.67P or 7857.0L

Table 8.2

8.2. Cost Model Results

The additional cost components required to determine the annual savings stream are presented for each case in Table 8.3. The only observed indirect savings to labor occurred for case E, where some 3.3 manhours per production run were eliminated from Station 5 positioning and tacking operations.

Case	ΔKI	ΔKA	ΔKQ
H	0	-123.3L	715.2L
HV	0	-296.6L	1480.3L
HV^*	0	-167.9L	900.7L
E	240.7L	-567.5L	741.8L

(manhours/year)

Table 8.3

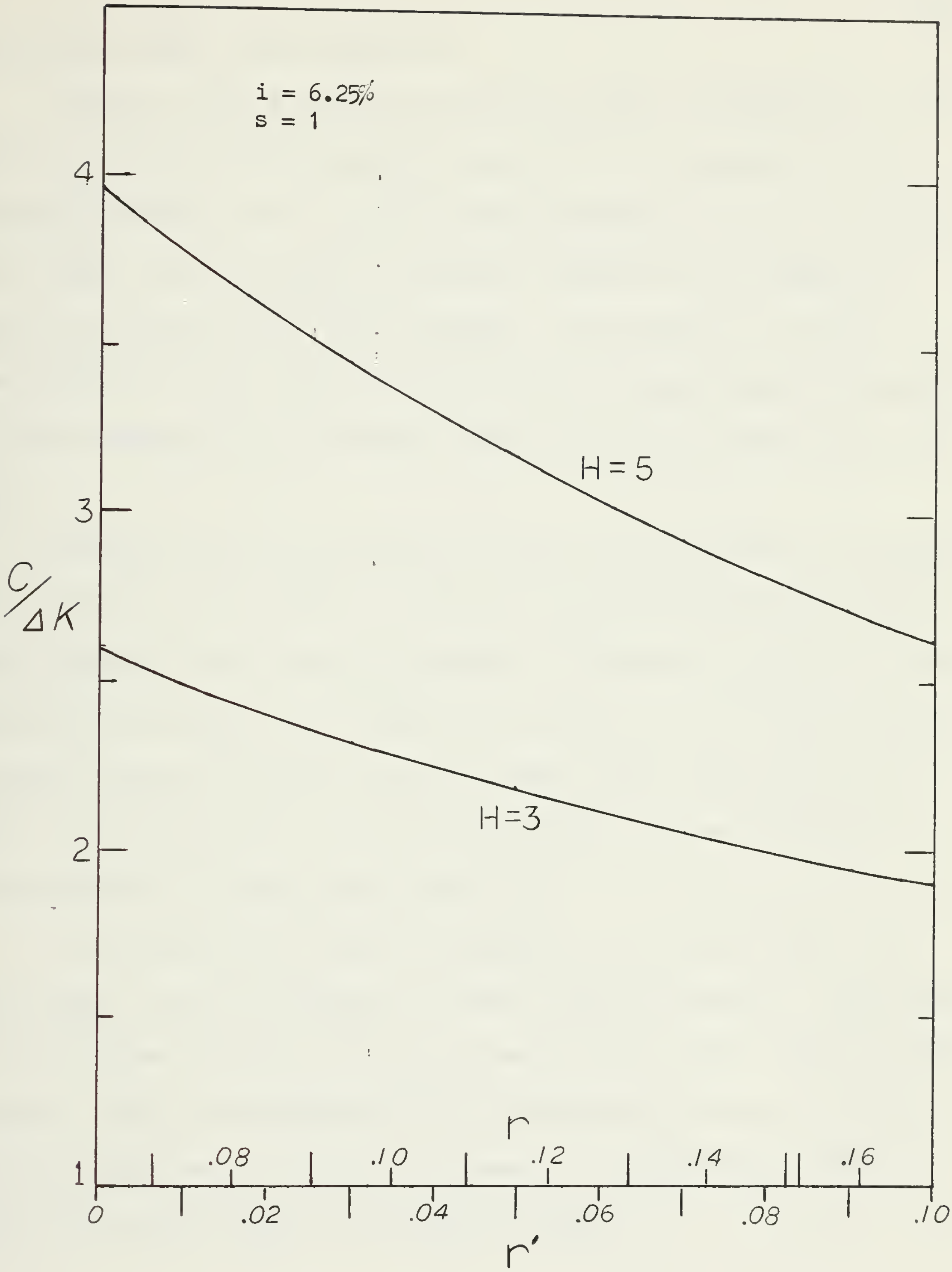
Hence the total annual savings stream for each alternative is:

Case	H	HV	HV^*	E	
ΔK	4627L	10,165L	5957L	8272L	(manhr/yr)
or	3240s	7120s	4170s	5790s	

where L=0.7s and s=shifts per day operated.

The result of expressing Equation (15) as a ratio of maximum acceptable investment cost to annual savings stream is shown, in Figure 8.5, as a function of interest rates, for given rate of inflation and single shift (s=1) operation. It is seen that the 5 year investment horizon provides for significantly greater investment cost than the 3 year horizon.

These curves were used to generate ratios of initial investment to base labor rate (C/R_L) as functions of effective interest rates for all



C/ΔK versus Interest Rates

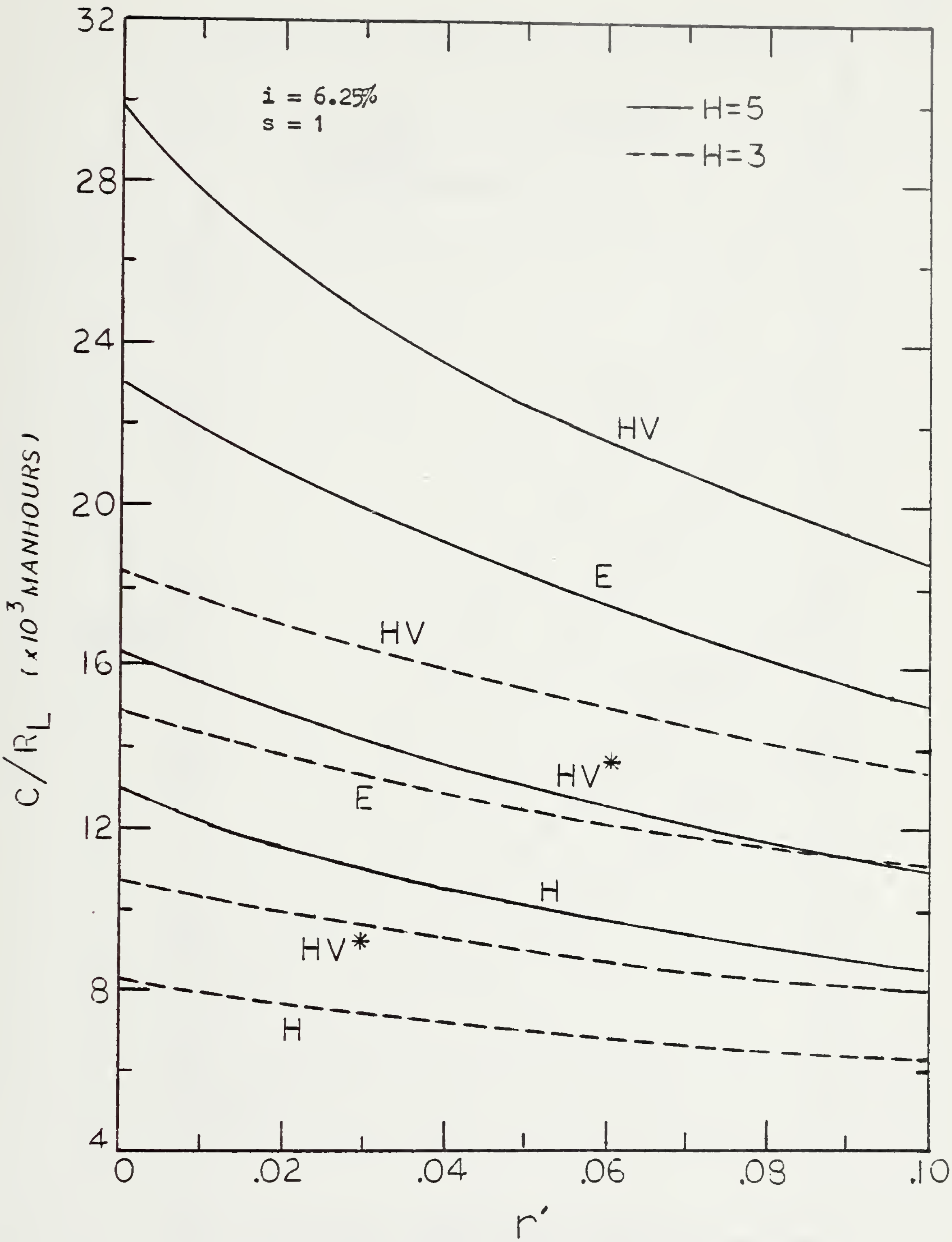
FIGURE 8.5

considered cases. See Figure 8.6.

Figures 8.7 and 8.8 portray maximum allowable investment costs in dollars for alternative systems as functions of s, equivalent shift per day operation, for 3 year and 5 year investment horizons, respectively. Fixed values of labor and interest rates have been assumed and are in line with current (1984) figures. The volatility of actual rates dictates that Figures 8.7 and 8.8 be considered sample scenarios of what maximum equity investment levels could be, not what they would be.

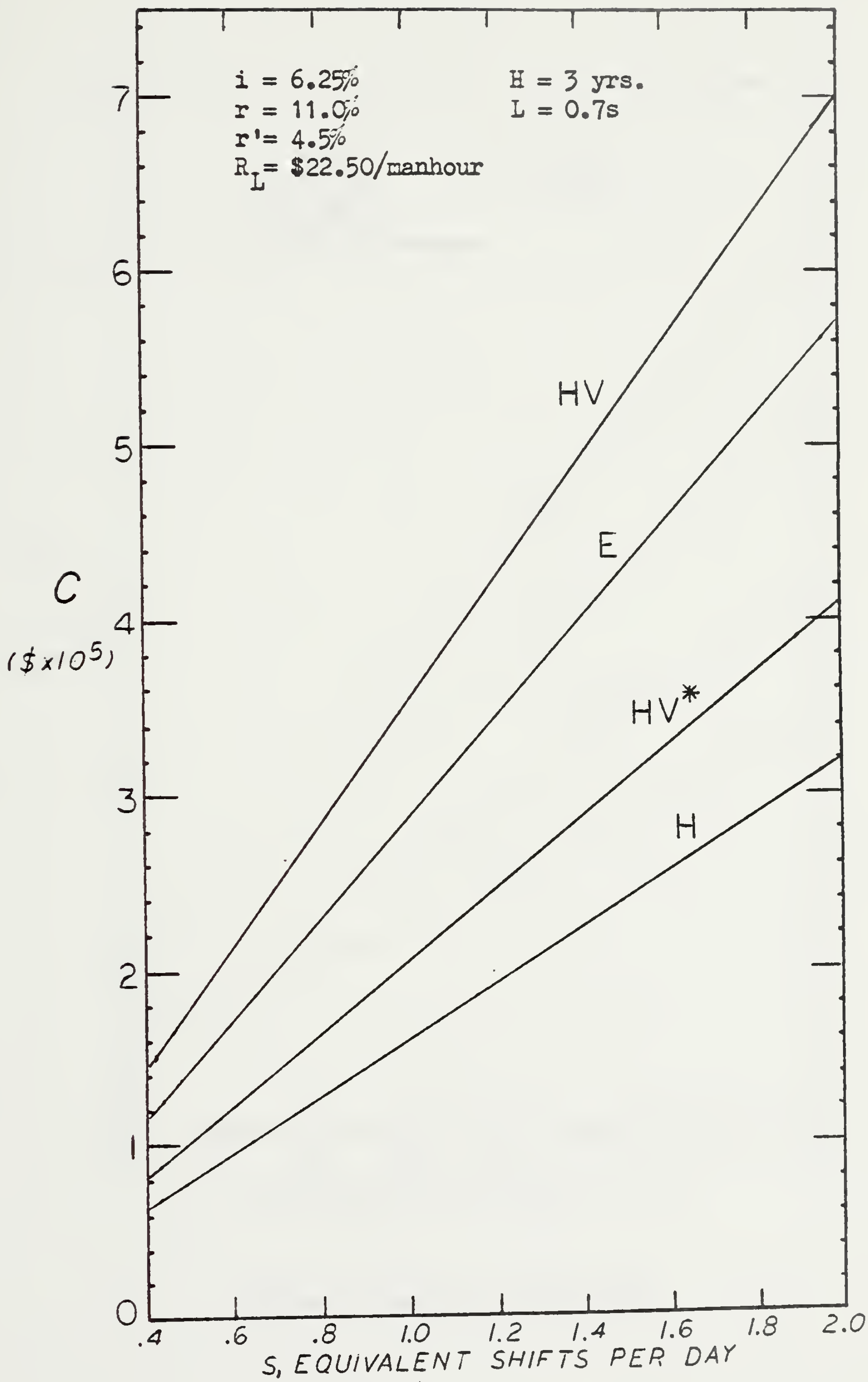
The significance of production volume is made clearer by converting the parameter s into physical amounts. Since the alternative systems have different production run durations, the physical capacity of module output varies among them. However, the variance is not large and the average equivalent annual output for single shift (s=1) operation is about 49 tank modules or 19,200 tons of panels. These amounts are representative of large-panel production.

To grossly estimate annual throughput of small-panel work that, for example, would be required for small surface combatant construction, it was assumed that the cost per ton was roughly 5 times that for large panels. (This was suggested by line manufacturers' data.) By this method, small panel capacity was guessed to be significantly less, maybe as low as 4,000 tons per shift per year.



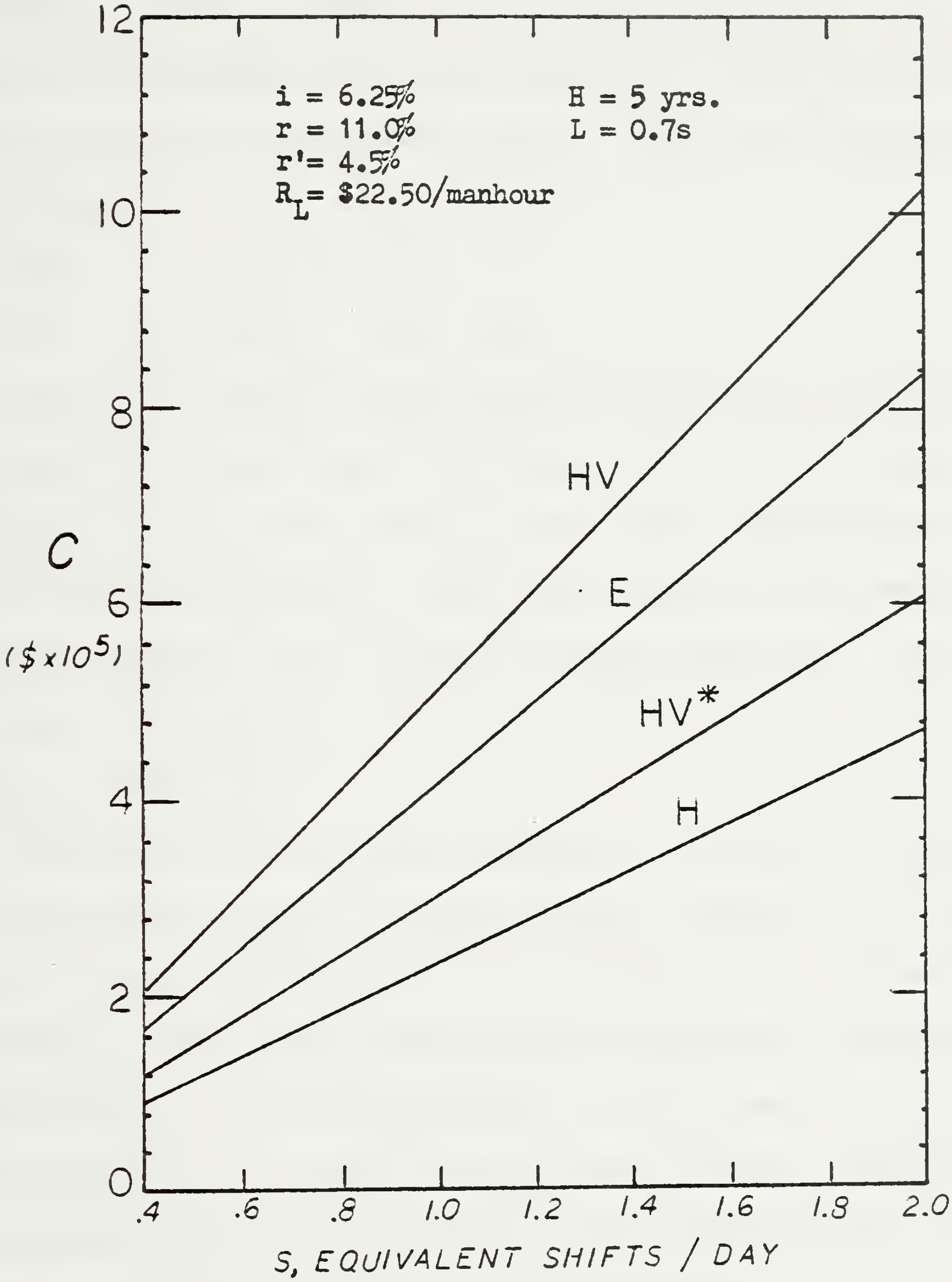
C/R_L versus r'

FIGURE 8.6



Maximum C versus s (H=3 years)

FIGURE 8.7



Maximum C versus s (H=5 years)

FIGURE 8.8

The cost benefit/technical capability indicator, Z, from Equation (7), was assessed for the four alternatives. While its numerical value is dependent on investment horizon and interest rate, the relation of values among alternatives is relatively constant. Arbitrarily normalized to case H, they were

Case:	H	HV	HV^*	E
Z:	1.0	0.91	1.29	0.39

Care must be taken to understand that the systems under comparison have significant technological differences. Cases H and E require x-y welding capability while cases HV and HV^* have additional ability in the z (vertical) direction. Case E has a greater requirement for collision avoidance, due to its need for human interaction. Yet it also needs no provision for the robot to produce vertical movement. Concepts HV and HV^* do.

Nevertheless these values do suggest several notions. Upgrading the capabilities of case H to provide vertical welding for all available vertical fillets (case HV) may not be a good idea. The Z parameter relationship between these two alternatives suggest that case HV pays a premium for its full vertical capacity. This is because it has excess capacity for all panels flowing through the line, except panel 5. The compromise system, HV^*, performing vertical work when time permits, appears to be an attractive alternative. This case, while less capable than HV, effectively reduces excess capacity. Because cases H and HV^* have identical TEAS values, the difference in their Z parameters suggests a premium that one might be willing to pay for upgrading case H with a vertical welding capability. Case E appears to

be the least favorable. Here, the notion of replacing efficient mechanized stiffener welding with robot welders is relatively unattractive for this assembly line.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

Major conclusions were drawn from the present study in several areas.

Robotic arc welding is beginning to find its way into American shipyards. Applications to structural subassembly work are being studied and developed; their prognosis for successful implementation is favorable. Conversely, the future of welding robots for erection work appears less optimistic, due to the extreme technological hurdles involved and the economic competition from increasingly sophisticated mechanized welding systems.

The chosen assembly stage process, flat panel assembly, as modelled, essentially utilizes welding robots as fixed equipment. In all alternative systems, the robot is fixed to the panel line, eliminating some of the flexible manufacturing capability of conventional robots. Consequently it was found that the productivity potential of robotic arc welding systems was affected by other assembly line processes. Fitting and tacking operations appear to be limiting factors in potential production throughput, not welding. Accordingly, it is believed that panel assembly systems employing advanced handling technology offer greater potential for incorporating robotic production welding. In other words robotic welding can only accomplish so much to upgrade total assembly line productivity, without investment in improvements at other process stations.

It is suggested that the attractiveness of arc welding robots for panel assembly could be enhanced by providing easier modularity or

improved mobility. The ideal system would not be constrained to the assembly line and could be readily used in other application areas. This concept should provide for interesting investigation in the future.

The analysis conducted for the flat panel assembly process, while crude,was useful in generating data for comparing alternatives. The notion of modifying the modelled assembly line for use of lattice welding robots does not appear economically favorable. Its desirability is further diminished by its need for human intervention. Among gantry systems, the balanced capacity alternative, (HV^*), with horizontal and vertical capability appeared preferable. (It is believed that consideration of pulse arc GMA welding would not significantly change this outcome.)

The success and degree of future robot application in assembly work will depend to a large part on future design practices. Structural concepts such as the HTS thin panel discussed in Chapter 5 could increase the use of welding robots in assembly, while others, such as the "no frame" concept [50], could potentially reduce their utility. Current designs can enhance robot introduction by devoting more effort to access improvement and detail simplification.

"Ball park" estimates of acceptable levels of initial investment suggest that long term implementation of robot welding systems to flat panel lines may be economically attractive. Such judgment is, of course, dependent on the actual projected costs and interest rates, perceived risk, financing, and level of production. It was shown that extension of the normal equity investment horizon, enhancing the acceptance of higher initial costs, may be required. However, American shipyard managers

can ill-afford to accept the additional risk involved, due to the weak position of their industry. Rapid technological change of robots, adaptive welding control systems, and competing automatic mechanized welders, further complicate investment decisions.

It can also be argued that continued technological advances may improve robot attractiveness by combining certain basic quality control functions, including dimensional control and documentation of fitup and weld bead, with the welding process. It is conceivable that future arc welding robots could employ diagnostic NDT techniques such as ultrasonic testing (UT) to insure weld quality in shipbuilding applications. Since inspection requirements can amount to some 20 to 50 percent of conventional welding process costs. The economic potential for research in this area is promising.

It is recommended that additional, more sophisticated process simulation be conducted, based on actual shipyard statistical data, to model panel assembly line operations with greater confidence. This should be done for a range of potential ship-product designs, not just simple tanker modules.

Based on surveyed information and analysis, panel assembly appears to be an application area of robotic arc welding that deserves more attention. Value of increased research sponsorship exists for Government and industry.

The concern for near term economic viability of U.S. shipyards, and technical and economic risk will probably require outside funding support from banks or Government agencies, for continued R & D efforts and actual plant acquisition. The Department of Defense Industrial

Modernization Incentives Program (IMIP) [5] can provide a source of direct equipment funding, should results of robotic welding R and D prove favorable. It is hoped that more thorough investigation of robotic welding for ship assembly is pursued and that Government participation in and support for such shipyard modernization is continued.

BIBLIOGRAPHY

[1] Department of Defense, 1982, Annual Report on the Status of the Shipbuilding and Repair Industry of the United States, 1983.

[2] Ramsay, R., "A Time for Shipbuilding Renaissance", Naval Engineers Journal, Vol. 95(5), pp. 33-63, September 1983.

[3] Maritime Administration, Technology Survey of Major U.S. Shipyards, 1978, 1979 .

[4] Deming, W., Quality,Productivity, and Competitive Position, MIT Center for Advanced Engineering Study, Cambridge, MA, 1982.

[5] Ramsay, R., "Approaches to Improving Shipbuilding Productivity" , Association of Scientists and Engineers of the Naval Sea Systems Command: 20th Anniversary Technical Symposium, 1983.

[6] Ohta, M., "The Construction and Welding of Sections in the New Shipyard", The Welding Institute: Structural Design and Fabrication in Shipbuilding, pp. 91-100, London, 18-20 November 1975.

[7] Kremers, J. and Nitzan, D., "Advanced Automation for Shipbuilding, Final Report", SRI International, November 1980.

[8] Fujita, Y., et al., "The Conditions for Application of Arc Welding Robots in Shipbuilding", IFIP: Computer Applications in the Automation of Shipyard Operation and Ship Design IV, pp. 283-292, 1982.

[9] Maciel, J. and Action, J., "Cincinnati Milicron T-3 Robot Final Report, Project Task No. 7-2", Todd Pacific Shipyards Corp., January 1984.

[10] Terai, K., "Welding Techniques in Shipbuilding", Welding Progress in Japan, 1972, Sanpo, Inc., pp.1-37, 1972.

[11] Anon., Current Welding Processes, American Welding Society, 1968.

[12] Salvendy, G. (ed.), Handbook of Industrial Engineering, Wiley, 1980.

[13] Engelberger, J.D., Robotics in Practice: Management and Applications of Industrial Robots, AMACOM, 1980.

[14] ________, ICAM Robotics Application Guide, Volume II, Air Force Wright Aeronautical Laboratories, Technical Report AFWAL-TR-80-4042, Vol. II, April 1980.

[15] Hewit, J.R. and Love, J.G., "The Application of Robotic Welding Technology to Shipbuilding", 13th International Symposium on Industrial Robots and Robots 7, pp. 6-70 to 88. Robotics International of SME, April 1983.

[16] Everett, H., "Summary of Navy Applications of Robotics Sponsored by the Naval Sea Systems Command", (Draft Paper), 1983.

[17] Reeve, R.C., "Self-programming robotic weld system", Developments in Mechanized, Automated and Robotic Welding, pp. P4-1 to 8, The Welding Institute, 1980.

[18] Morris, G.J. and Apps, R.L., "Programmed Control of MIG Welding Parameters", Welding and Metal Fabrication, pp. 487-493, October 1977.

[19] Prinz, F.B. and Hoburg, J.F., "Sensors for Seam Characterization in Robotic Arc Welding", Robotics Research and Advanced Applications, pp. 279-287, ASME, 1982.

[20] Verdon, D.C., et al., "Adaptive Welding Control Using Video Signal Processing", Developments in Mechanized, Automated and Robotic Welding, pp. P29-1 to 11, The Welding Institute, 1980.

[21] Kremers, J.H., et al., "Development of a Prototype Robotic Arc-Welding Work Station", Final Technical Report, NAVSEA Report No. S50002-83, SRI International and Todd Pacific Shipyards Corporation, May 1983.

[22] Nakamura, T., et al., "Development of Welding Robots and their Practical Application", Proceedings of International Conference on Welding Research in the 1980's, pp. 245-249, Japan Welding Research Institute, 1980.

[23] Metzbower, E.A., "Laser Welding of Mild Streel at NIROP", Final Report, NRL Report 8644, Naval Research Laboratory, Minneapolis, 14 February 1983.

[24] Wilson, E., "Welding Technology Data Sheet 60: Metal inert gas (MIG) arc welding-part 4", Welding and Metal Fabrication, pp. 165-172, May 1982.

[25] Watanabe, I., et al., "Applicability of Large Current MIG Arc Welding Technique", Proceedings of International Conference on Welding Research in the 1980's, pp. 43-48, Japan Welding Research Institute, 1980.

[26] Koshiga, F., et al., "High Productivity One-sided MIG-welding Technique," Structural Design and Fabrication in Shipbuilding, pp. 117-130, The Welding Institute, 1976.

[27] Weber, J., "Heavy Equipment Welding Systems Go Beyond Robotics", Welding Journal, pp. 50-51, September 1982.

[28] Hill, J.W., "New Applications for Industrial Robots in Shipbuilding", REAPS Technical Symposium, Philadelphia, PA., pp. 403-414, October, 1980.

[29] Kihara, H., et al., "Some Examples of Robot in Shipbuilding", IFIP: Computer Applications in the Automation of Shipyard Operation and Ship Design II, pp. 403-414, June 1976.

[39] Maciel, J.P. and Acton, J.B., "Unimation Apprentice Welding Robot for Shipyard Application, Final Report", Todd Pacific Shipyards Corp., December 1983.

[31] ________, "CRC M-1000", Sales brochure, Crutcher Resources Corporation, 1983.

[32] Chiaromonte, F., "Robotisation and Quality of Working Life: A Case Study in Italian Industry", Proceedings of the 2nd European Conference on Automated Manufacturing, pp. 141-147, IFS Conferences, Ltd., 1983.

[33] von Gizycki, R., "Social Conditions for and Consequences of the Use of Industrial Robots in Five Factories", 10th International Symposium on Industrial Robots, pp. 619-627, Robotics International of SME, 1980.

[34] Hunt, H.A. and Hunt, T.L., Robotics: Human Resource Implications for Michigan. The W.E. Upjohn Institute for Employment Research, 1982.

[35] Aron, P., "Robots Revisited: One Year Later", Exploratory Workshop on the Social Impacts of Robotics, pp. B36-B37, U.S. Congress, Office of Technology Assessment, 1982.

[36] Masubuchi, K., Analysis of Welded Structures, Pergamon Press, 1980.

[37] Becker, H. and Callao, A., "Compressive Strength of Ship Hull Girders, Part III-Theory and Additional Experiments", U.S. Ship Structures Committee Report SSC-267, 1977.

[38] Satoh, K., Matsui, S., Terai, K., and Iwamura, Y., "Water-cooling Effect on Angular Distortion Caused by Process of Line Heating in Steel Plates", Journal of the Society of Naval Architects in Japan, No. 126, pp. 446-458, 1969.

[39] Bannerman, D. and Jan H., "Analysis and Design of Principal Hull Structure", Chapter VI, Ship Design and Construction, SNAME, pp. 255-257, 1980.

[40] Tsai, C-L, et al., "Review of Fillet Weld Strength Parameters for Shipbuilding", U.S. Ship Structures Committee Report SSC-296, 1980.

[41] American Bureau of Shipping, Rules for Building and Classing Steel Vessels, 30.9.2, 1982

[42] Srivastava, U.K., et al., Quantitative Techniques for Managerial Decision Making, Wiley, 1983.

[43] Pritsker, A.A. and Happ, W.W., "GERT: Graphical Evaluation and Review Technique; Part I. Fundamentals," The Journal of Industrial Engineering, vol. XVII (5), pp. 267-274, May 1966.

[44] Pritsker, A.A., and Whitehouse, G.E.,"GERT: Graphical Evaluation and Review Technique; Part II. Probabilistic and Industrial Engineering Applications", The Journal of Industrial Engineering, Vol. XVII(6), pp. 293-301, June 1966.

[45] Nakata, M.Y., "Out-of-Position Welding of 5000 Series Aluminum Alloys Using Pulse GMAW Power Sources, Final Report", Todd Pacific Shipyard Corp., January 1984.

[46] Chapman, K.R., et al., "Production Kindliness in StaT products carriers", The Welding Institute: Structural Design and Fabrication in Shipbuilding, pp. 215-226, London, 18-20 November, 1975.

[47] Lindeburg, M.R., Engineer in Training Review Manual, Professional Publications, 1982.

[48] Kauffman, W.W., "Defense Issues and Budgets", Class notes for MIT Course 17.498, Spring, 1984.

[49] Gustavson, R.E., "Engineering Economics Applied to Investments in Automation", SME: Proceedings of Second International Conference on Assembly Automation, 1981.

[50] Nappi, N.S., et al., "The 'No Frame' Concept - Its Impact on Shipyard Cost", Naval Engineers Journal, Vol. 96(3), pp. 218-232, May 1984.

207074

Thesis
K795 Koreisha
The applications of robotic arc welding to shipbuilding.

Thesis 207074
K795 Koreisha
The applications of robotic arc welding to shipbuilding.

thesK795
The application of robotic arc welding t
3 2768 002 10494 5
DUDLEY KNOX LIBRARY